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Events leading to anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases

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ABSTRACT

Background The authors have recently identified three main mechanisms for anterior cruciate ligament (ACL) injuries among World Cup (WC) alpine skiers, termed as "the slip-catch", "the landing back-weighted" and "the dynamic snowplow". However, for a more complete understanding of how these injuries occur, a description of the events leading to the injury situations is also needed.

Objective To describe the skiing situation leading to ACL injuries in WC alpine skiing.

Methods Twenty cases of ACL injuries reported through the International Ski Federation Injury Surveillance System (FIS ISS)for three consecutive WC seasons (2006–2009) were obtained on video. Ten experts (9 WC coaches, 1 former WC athlete) performed visual analyses of each case to describe in their own words, factors they thought may have contributed to the injury situation related to different predefined categories: (1) skier technique, (2) skier strategy, (3) equipment, (4) speed and course setting, (5) visibility, snow and piste conditions and (6) any other factors.

Results Factors related to the three categories, namely skier technique, skier strategy, and visibility, snow and piste conditions, were assumed to be the main contributors to the injury situations. Skier errors, technical mistakes and inappropriate tactical choices, were the dominant factors. In addition, bumpy conditions, aggressive snow, reduced visibility and course difficulties were assumed to contribute.

Conclusion Based on this systematic video analysis of 20 injury situations, factors related to skier technique, skier strategy and specific race conditions were identified as the main contributors leading to injury situations.

INTRODUCTION

The risk of injury in World Cup (WC) alpine skiing is high.[1] During the 5-month International Ski Federation (FIS) WC season, one in every three skiers sustains a time-loss injury, and during the competition the incidence is 9.8 injuries per 1000 runs.[1] Similar to recreational skiers,[2] the most common injury in professional skiers is to the knee, and the most frequent specific diagnosis is rupture of the anterior cruciate ligament (ACL).[3]

Understanding the mechanism of such injuries is essential for their prevention.[4] Recently, we described the mechanisms of ACL injury based on systematic analyses of videos from 20 injury cases.[5] This was the first study to describe the mechanisms of ACL injuries among professional ski racers (WC alpine skiers), and three distinctive mechanisms were identified and termed "the slip-catch", "landing back-weighted" and "the dynamic snowplow".

Both the slip-catch and the dynamic snowplow mechanisms are markedly different from the mechanisms described among recreational skiers.[6] In contrast to recreational skiing, professional ski racing requires extreme skiing skills, experience and fitness,[7] as well as more aggressive equipment (the ski-binding-boot system).[8] The snow conditions and the terrain are obviously more challenging.[9]

To fully understand the mechanisms of these ACL injuries, a description of the events leading to the injury situations is needed.[4] Injury causation is probably multifactorial and identifying the factors that contribute to the chain of events that put the athlete in a vulnerable position could provide important clues to prevent injuries. The aim of this study was to describe the skiing situation leading to ACL injuries in the WC alpine skiing based on a technical analysis of the video recordings.

METHODS

Injury and video recording

We obtained video recordings of injuries reported through the FIS Injury Surveillance System (ISS) of three consecutive WC seasons (2006–09). The FIS ISS injury registration was based on interviews with all athletes or coaches/medical staff from 10 of the largest WC teams.[1] In total, 281 injuries were reported among the WC alpine skiers during this time period, 209 of these occurring during the WC and the World Ski Championship (WSC) events (figure 1). Of these, 21 knee injuries were reported – and later confirmed with the team's medical staff – as total ACL tears. A majority of the ACL injuries occurred during competition (n=18), while the remaining few sustained during the official training (n=3).[5]

The television producer, Infront (Italy), provided the video footage of the entire run for each of the confirmed ACL injuries during the competition. Additional footage of injuries from the official training and the WSC were obtained directly from the FIS or through personal contacts within the teams. In this way, we managed to capture all 21 ACL injuries on video. In total, 11 injuries were captured from one camera angle, six injuries from two camera angles and four injuries from three camera angles. One out of the 21 injury cases had to be excluded, as the

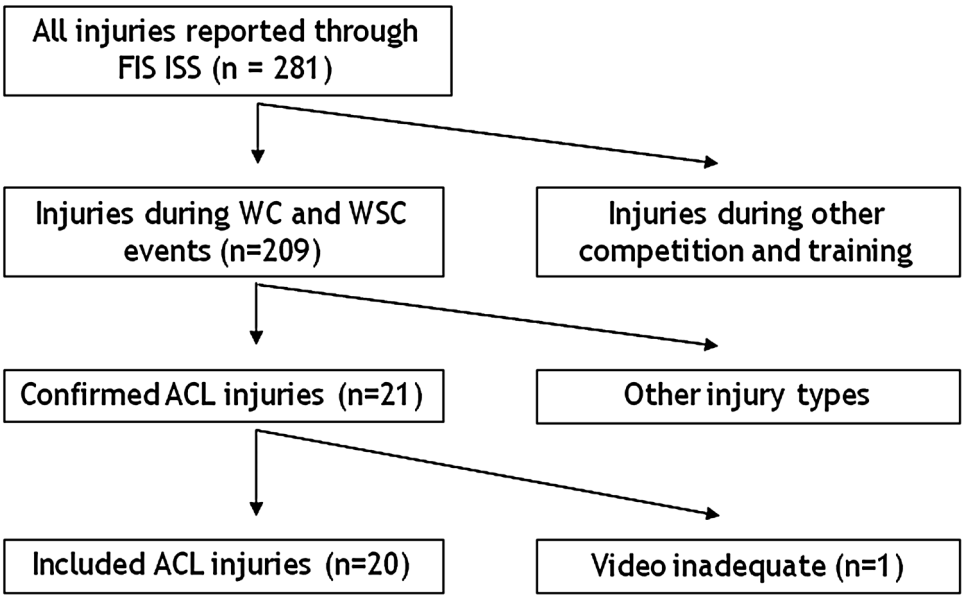

Figure 1 Flow chart showing the process to identify videos of ACL injuries in the WC alpine skiing based on injury registration through the FIS ISS (2006–09).

skier was partly occluded by the terrain in the video, when the injury happened.

Infront also provided footage of runs by non-injured skiers, in order to compare the injury to the no-injury situations in the competition. The process to select the matched controls was described previously by Bere *et al* (2011).

Video processing

We received the video footage as analog video files on Beta SP (n=16) or as digital files in varying formats (n=5). By using a video editing program (Final Cut Pro, version 6.0.5; Apple, Cupertino, California, USA), we edited two versions of each run, one full version showing the entire run and one short version showing the specific injury situation (including several gates, prior to the injury situation and until the skier came to a full stop). Analog files were digitised to QuickTime (.mov) files in 4:3 format (Episode Engine Admin, version 5.0; Apple) with a DV 25 PAL codec. We used QuickTime Player 7 (Apple) to review the videos.

Video analysis

We invited 14 experts (10 current WC coaches, three former WC coaches , the current national team's coaches and 1 recently retired WC ski racer) to review the videos independently, in order to describe in their own words, factors they thought may have contributed to the injury situation. They were asked to focus on the skiing situation prior to the time of injury to describe the events leading to the injury situation, as the injury mechanisms themselves have been described in detail previously.[5] These included the following predefined categories: (1) skier technique, (2) skier strategy, (3) equipment, (4) speed and course setting, (5) visibility, snow and piste conditions and (6) any other factors. They were also asked to review the control tape(s) and describe in their own words, any observations they felt were relevant to understand the causes of injury. The form included open questions to obtain as much expert information as possible. The coaches completed one analysis form for each injury case, and they were provided with information of sex and injured side for each case.

The experts were also provided with video files on a memory stick and analysis forms in a folder. Ten coaches completed the analyses, seven in our laboratory, three on their own, while the remaining four did not respond despite reminders. Each coach used 3–6 h to review the videos carefully and complete the forms.

Data reporting

We reported the results as the number of coaches with statements in each specific category, the number of statements within each category and the number of injury cases where a specific factor was assumed to have contributed to the injury situation.

RESULTS

Of the six categories included in the analysis, three were identified as main contributors leading to the injury situation: (1) skier technique, (2) skier strategy, and (3) visibility, snow and piste conditions (table 1). For each of the ACL injury mechanisms, the slip-catch, the dynamic snowplow and the landing back-weighted, factors in the above-mentioned three categories dominated as main contributors to the injury situation. However, the factors identified in the skier technique and skier strategy differed between each of the injury mechanisms. Nevertheless, technical mistakes and inappropriate tactical choices were assumed to be the main factors leading to the injury situations across the three main mechanisms.

Skier technique and skier strategy

Slip-catch

For the 10 cases classified as slip-catch injuries, the skiing situation prior to the injury was consistently characterised by the technical and tactical mistakes, where the skier came to be out of balance backwards/inwards, losing pressure on the outer ski. In five of the slip-catch cases, the racer did not manage to absorb terrain changes prior to injury. The racer was passive or hesitated, which the slope/course did not

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Table 1 The total number of coaches who made statements in each of the six categories for the different injury mechanisms

Injury mechanism	Technique	Strategy	Equipment	Speed, course setting	Visibility, snow, piste conditions	Any other factors	Total
Slip-catch (n=10)	89 (173)	55 (75)	15 (15)	9 (9)	50 (72)	11 (11)	229 (355)
Dynamic snowplow (n=3)	21 (24)	12 (15)	9 (9)	2 (2)	17 (28)	5 (5)	66 (83)
Landing back- weighted (n=4)	35 (50)	19 (22)	4 (4)	2 (2)	14 (16)	6 (6)	80 (102)
Other (n=3)	16 (27)	16 (17)	7 (7)	4 (4)	9 (13)	8 (10)	60 (78)
All (n=20)	161 (274)	102 (129)	35 (35)	17 (17)	90 (129)	30 (32)	435 (616)

For example, for the slip-catch cases, a maximum value for the category named technique would be 100 (10 coaches × 10 cases). In parenthesis, the number of statements made in each of the six categories is shown. There was no limitation on the number of different statements in each category each coach could make.

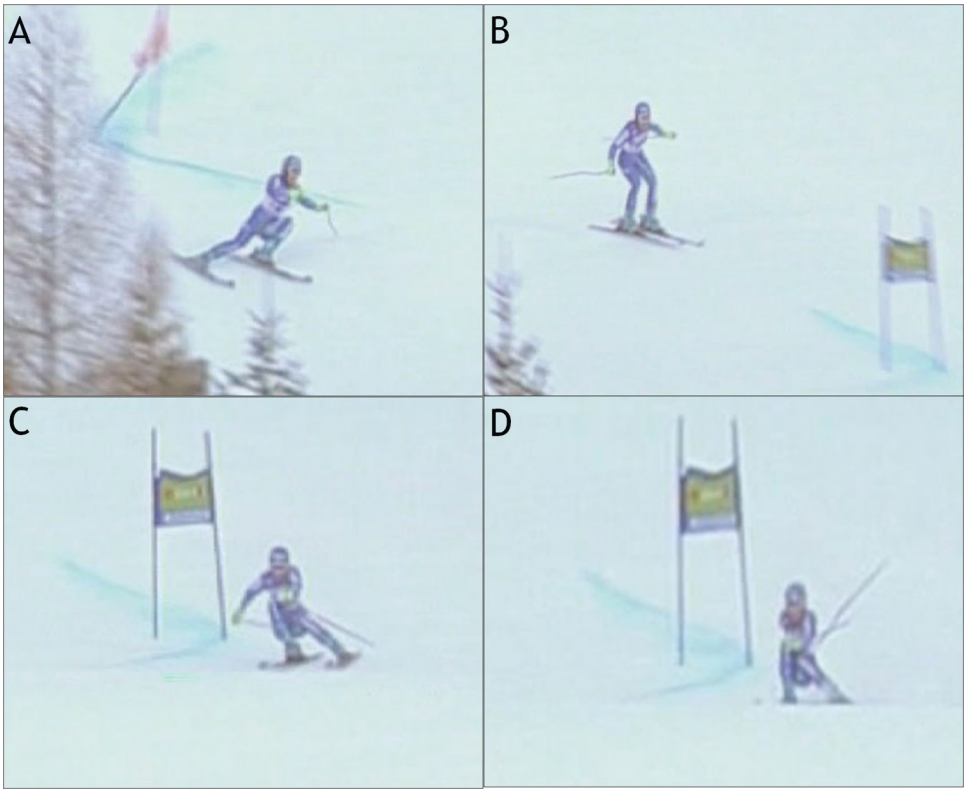

Figure 2 Events leading to slip-catch mechanism (ACL injury to the left knee): (A) (− 1.32 s), the racer is late on line with an inappropriate position over the outer ski. (B) (− 0.62 s), she goes too directly into the next gate where she should have invested more line and, trying to adjust by skidding rather than carving through the turn (C) (− 0.24 s), the racer leans too much inwards/backwards and loses pressure on the outer ski. She is being pushed down into the compression in a passive/defensive posture. (D) (index frame), the outer ski catches the inside edge abruptly, forcing the left knee into valgus and internal rotation.

allow. He/she was too late timing the transition, from flat to steep terrain (break-over points) or from steep to flat terrain (compressions). In addition, the racer was slightly late on the ideal line (under time pressure), thus he/she had a more direct approach into the next turn and was forced to use compensatory turning techniques to manage the gate. This resulted in an even more backwards/lower position initiating too much inside lean. Being out of balance backwards/inwards, the skier lost pressure on the outer ski. A more detailed description of two of these cases is shown in figures 2 and 3.

In two other slip-catch cases, the racer did not absorb the changes in the rhythm of the course, set prior to injury. The result was again time pressure and a very direct line into the next gate. The racer came out of balance backwards/inwards and lost pressure on the outer ski. A more detailed description of one of these cases is shown in figure 4.

In the three final slip-catch cases, the racer initiated the turn too early. He was unable to find the appropriate standing position over the outer ski and came out of balance backwards/inwards, losing pressure on the outer ski. A detailed description of one of these cases is shown in figure 5.

Landing back-weighted

For the landing back-weighted mechanism (n=4), the skiing situation prior to the injury was characterised by poor jumping technique and incorrect tactical decisions which resulted in an uncontrolled flight with subsequent landing on the ski tails. The skier was in a backward-leaning position at take-off and did not move forward into the hill. He still had pressure on the skis at take-off, which caused a "crossbow effect" into the air. These cases were also characterised by tactical mistakes, such as late timing of movements into the jump, wrong timing of the take-off point, inappropriate line/trajectory into the jump and/or inappropriate judgment of speed related to the jump profile. A more detailed description of two of these cases is shown in figures 6 and 7.

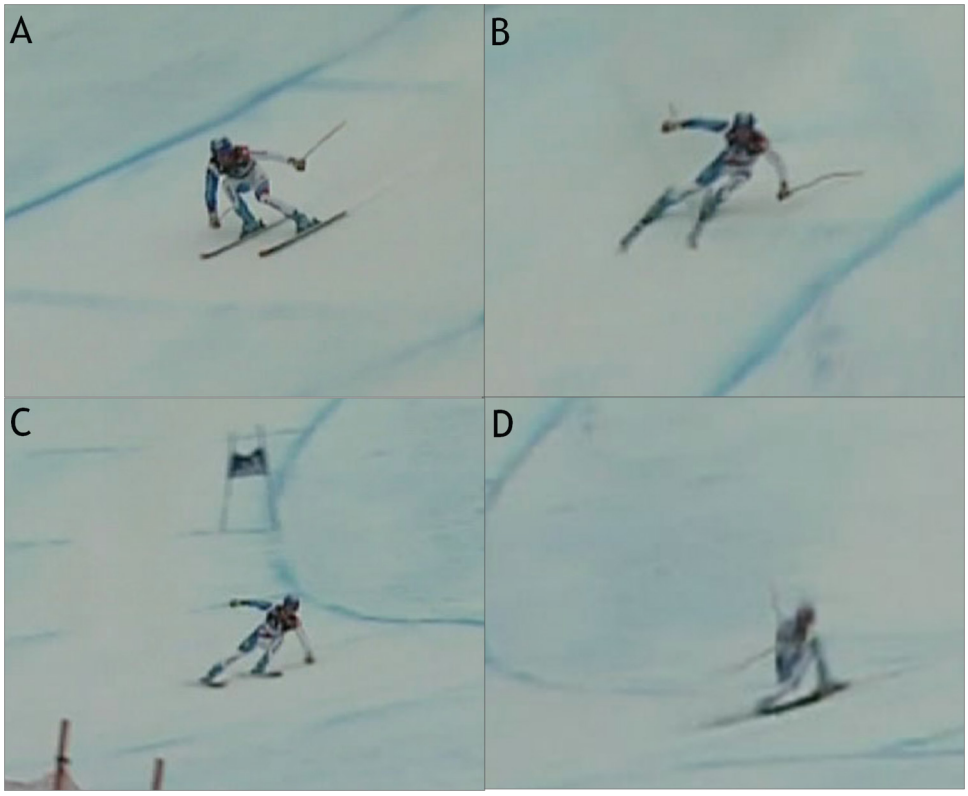

Figure 3 Events leading to slip-catch mechanism (ACL injury to the right knee): (A) (− 2.16 s), the racer is late in line and not in a balanced position. (B) (– 1.44 s), he goes too directly into the next gate and leans too much inside initiating the turn. He is late timing his movements during the turn, skiing passively. (C) (− 0.48 s), the racer goes directly into a compression in an unbalanced position backwards/inwards and loses pressure on the outer ski, unable to absorb the terrain transition. (D) (index frame), the outer ski catches the inside edge abruptly, forcing the right knee into valgus and internal rotation.

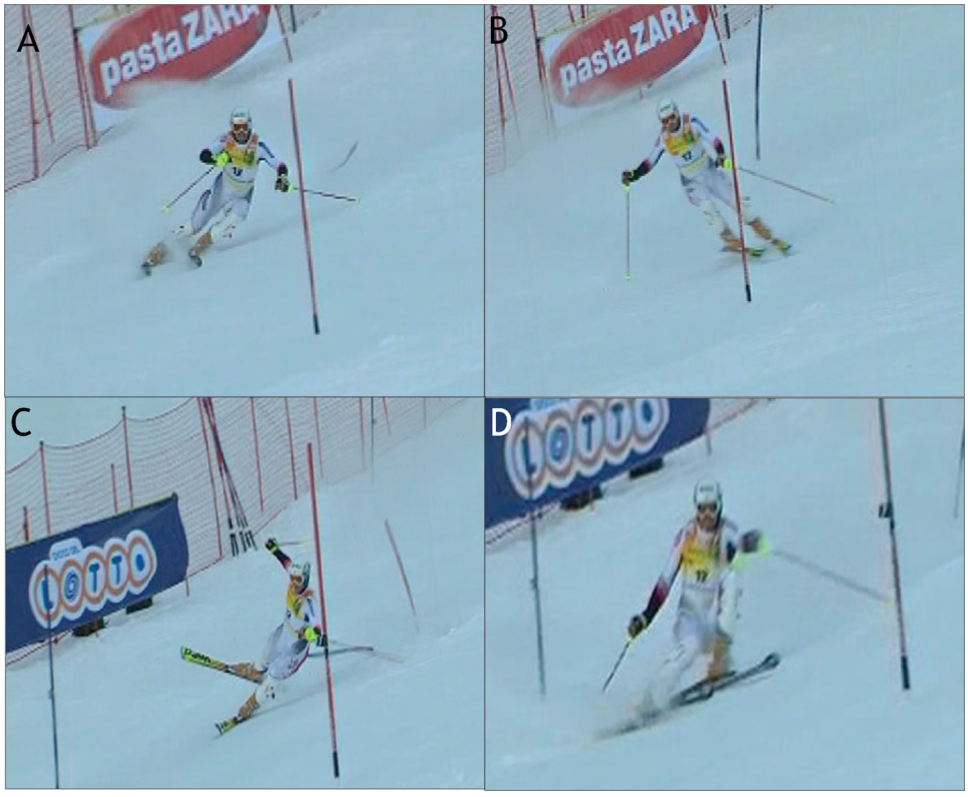

Figure 4 Events leading to slip-catch mechanism (ACL injury to the right knee): (A) (− 1.92 s), the racer is late in line after a change of rhythm in the set course. (B) (− 1.52 s), he goes too directly into the entrance of a hairpin in a backwards position. (C) (− 0.40 s), he tries to manage the next gate with an inner ski turn and loses snow contact with the outer ski. (D) (index frame), trying to recover from the unbalanced position, the outer ski catches the inside edge abruptly, forcing the right knee into valgus and internal rotation.

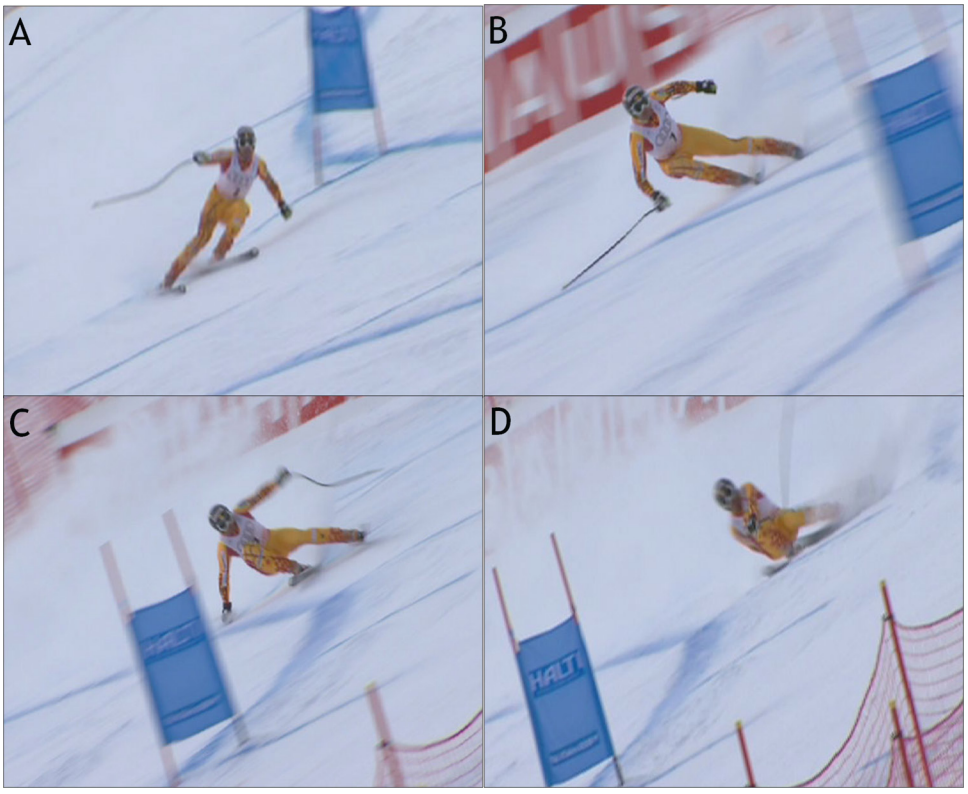

Figure 5 Events leading to slip-catch mechanism (ACL injury to the left knee). (A) (− 2.40 s), the racer is too low in line coming out of a compression, skiing hesitatingly. (B) (− 0.68 s), he needs to set up the skis to make the next turn, initiating the turn too early and has to wait without pressure on the skis. (C) (− 0.28 s), the racer is out of balance backwards/inwards and does not find the correct standing position on the outer ski when initiating the turn. (D) (index frame), the outer ski catches the inside edge abruptly, forcing the left knee into valgus and internal rotation.

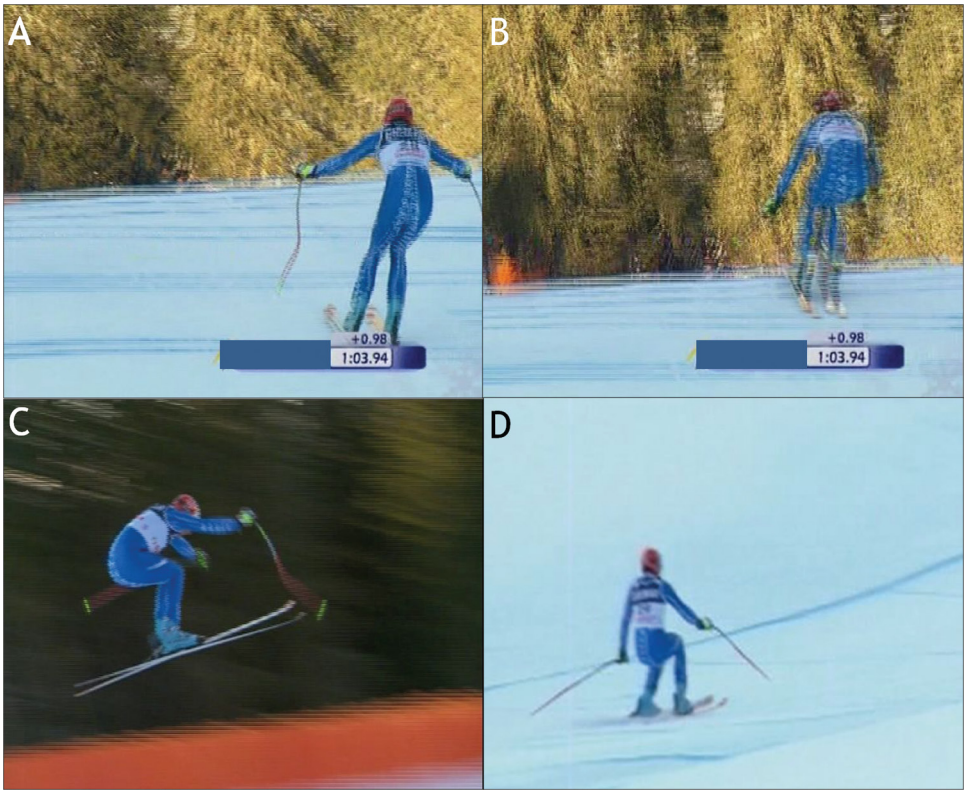

Figure 6 Events leading to landing back-weighted (ACL injury to the left knee): (A) (− 2.16 s), the racer is late in timing of movements into the jump and timed his take-off badly. (B) (− 2.00 s), he is in a backward-leaning position at take-off. (C) (− 0.68 s), uncontrolled flight due to poor jumping technique and incorrect tactical decisions. (D) (index frame), he tries to recover from a backward-leaning position after landing on the ski tails with almost straight knees.

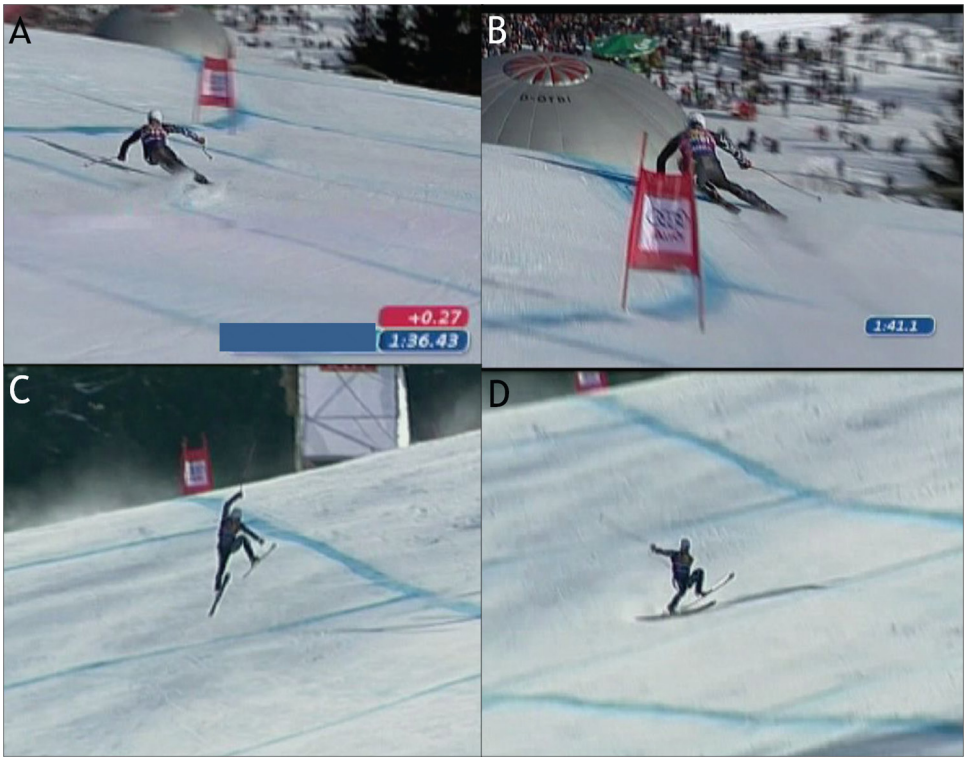

Figure 7 Events leading to landing back-weighted (ACL injury to the right knee): (A) (− 2.08 s), the racer has a too straight line and too little change of direction into the turn entering the traverse. (B) (− 1.24 s), he has a backward position, does not follow the terrain and has too much pressure on the skis at take-off. (C) (− 0.36 s), uncontrolled flight due to poor jumping technique and incorrect tactical decisions. (D) (index frame), he lands on the ski tail with an almost straight right knee.

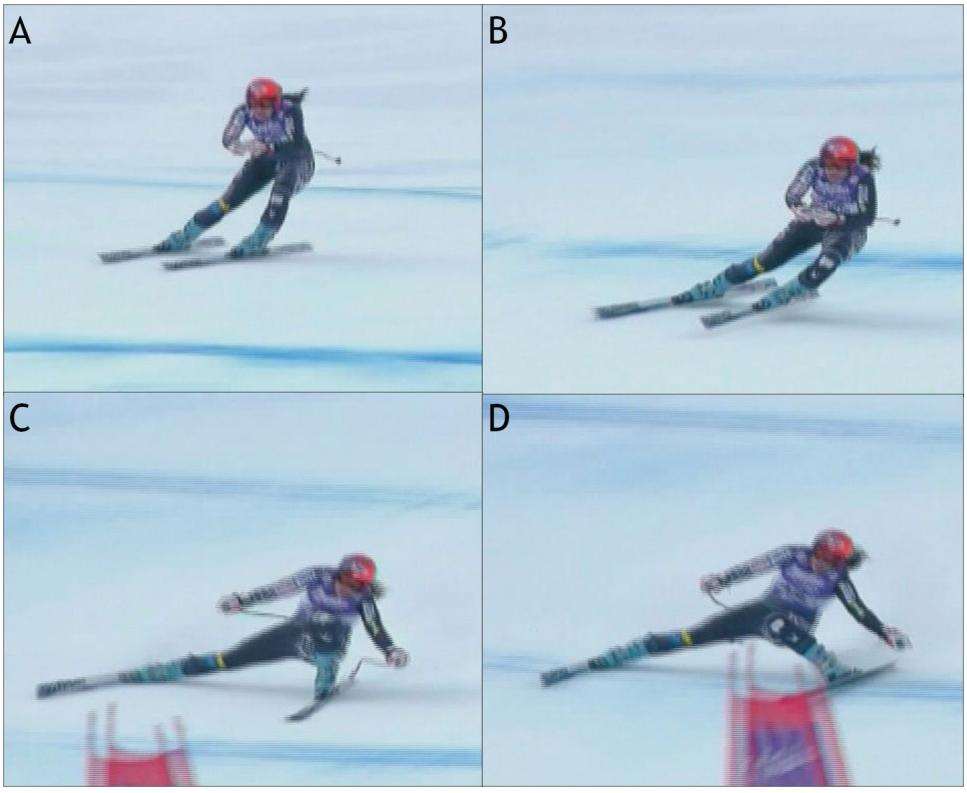

Figure 8 Events leading to dynamic snowplow mechanism (ACL injury to the left knee): (A) (− 0.56 s), the racer initiates a left hand turn too early with too much inside lean. (B) (− 0.28 s), she loses pressure on the outer ski, and in an unbalanced standing position backwards/inwards, she hits some small bumps on the course. (C) (− 0.12 s), due to inappropriate weight distribution and ski edging angle, the inner ski rolls from the outside edge to the inside edge. (D) (index frame), the racer ends up in a snowplow position, forcing the left knee into internal rotation and valgus.

Table 2 The number of statements made by the 10 coaches for the 20 cases related to factors within the categories visibility, snow and piste conditions

Visibility, snow and piste conditions		Statements	Cases
Visibility	Flat light	18	8
	Poor blue colouring	7	6
	Bad visibility	12	2
	Fog	4	2
Snow	Aggressive snow	11	9
	Icy conditions	14	7
	Inconsistent snow conditions	4	2
	Soft/accumulated snow	5	2
Piste	Small bumps	22	11
	Challenging piste/jump for the racers	13	9
	Not well prepared jumps/spill zones	17	4
	Flat landing	1	1
	Course too smooth	1	1

There was no limitation on the number of different factors each coach could identify. The table also shows the number of injury cases where these specific factors were assumed to contribute to the injury situation.

Table 3 The number of statements made by the 10 coaches for the 20 cases related to factors within the categories equipment, speed and course setting and other factors

Equipment, speed and course setting and other factors		Statements	Cases
Equipment	Too aggressive skis and boots	15	12
	Too aggressive skis	9	7
	No binding release	6	3
	Incorrect ski and boot setup	5	3
Speed and course setting	Challenging course set for the racers	8	5
	High speed	9	5
Other factors	Inexperienced/young racer	7	7
	Previous injuries	5	4
	Physical conditioning	5	4
	Psychological factors	5	4
	Safety net, gate panels	6	2
	High bib number	2	2
	Bad luck	2	2

There was no limitation on the number of different factors the coaches could identify. The table also shows the number of injury cases where these specific factors were assumed to contribute to the injury situation.

Dynamic snowplow

For the dynamic snowplow mechanism (n=3), the racer ended up in a snowplow position with inappropriate pressure on the inside edge at the time of injury. Prior to injury, the racer had too straight a line into a downhill turn (n=2) or initiated the turn too early (n=1), leading to too much inside lean at the initiation of the turn and loosing pressure on the outer ski. In an unbalanced standing position, the racer was not able to react to sudden changes in snow and piste conditions. In two of the cases, the racer hit some loose accumulated snow outside the ideal line after the turn, and in the third case, the racer hit some small bumps on the course. In all cases, the racer was unable to control the skis due to an inappropriate weight distribution and ski edging angle. A detailed description of one of these cases is shown in figure 8.

Visibility, snow and piste conditions

In total, the coaches made 129 statements within the category visibility, snow and piste conditions (table 2). The main factor related to the piste conditions was the small bumps on the course. In 8 of the 10 slip-catch cases, bumpy conditions were assumed to contribute towards an unbalanced position and/or catching the edge. Another main factor was that the piste/jump was challenging. In three of the four landing back-weighted cases, the jump was reported to be one of the most challenging on the WC tour. In six other injury cases, the injury happened in a rough and difficult section of the course, such as in a traverse or compression. Of factors related to snow conditions, aggressive snow was reported to contribute in 5 of the 10 slip-catch cases, and this kind of snow was described as hard, dry and risky for catching an edge. Icy conditions (water-prepared or injected snow) were also reported to contribute to the injury situation in half of the slip-catch cases. Regarding visibility, flat light and poor blue colouring of the lines and take-off points were dominant factors contributing to injury.

Equipment, speed and course setting

Within the category equipment, the coaches made 35 statements, in total (table 3). The main factor reported was the aggressiveness of the skis and/or boots, that is due to the material properties and the tuning of the equipment, the ski-binding-boot system, that may lead to a high load transfer to the body, if the athlete is unable to control it. The other factors mentioned were the no binding release and the incorrect ski and boot setup. Incorrect ski and boot setup means that the tuning of the skis and boots (including canting of the boot sole) is not optimised according to the athlete's physical ability, skiing technique and race conditions, such as the snow surface and course setting. Regarding speed and course setting, the coaches reported factors related to challenging course setting and high speed (table 3).

DISCUSSION

This is the first study aiming to identify the factors related to the skiing situation, leading to ACL injuries in the WC alpine skiing. The principal finding was that skier errors (ie, factors related to the skier technique and strategy) and specific race conditions were the main contributors to the injury situations.

Methodological considerations

Visual analysis of the video recordings is dependent on the video quality, and this may affect the interpretation. Thus, we strived to obtain the best possible video quality through video processing. However, 11 of the 20 injury situations were captured from only one camera angle. Although several camera angles would help in the interpretation of the skiing situation, the authors feel confident that this was not a substantial limitation for the coaches.

The challenge in utilising the analysis forms to obtain information based on video analyses, is the use of categories and definitions, which could limit the information obtained from the experts. The authors, therefore used one open question for each category in order not to bias their views. We experienced that some factors were mentioned across the different categories, which made it more difficult to summarise the results. However, this may reflect the fact that injury causation is most often multifactorial and complex.[4] There is probably no single solution which will prevent ACL injuries from occurring, thus

all the suggested factors may have a potential to reduce the risk of injury. We also have to keep in mind that there was no limitation on the number of different factors in each category the experts could identify, and they were not asked to rank the factors according to their priority. Therefore, the most frequently reported factors are not necessarily the most important.

According to the experts, skier errors (ie, factors related to the skier technique and strategy) dominated as the main contributors. However, we have to keep in mind that the assessment of the videos was subjective and qualitative, and the review of the skiing situation prior to the injury may have been influenced by the perspective of the experts. Their specific areas of knowledge and competence are the skiing technique and strategy, and it may be that other experts, for example, race organisers or equipment designers, would have focused on other factors.

Another limitation is that we do not know how often these factors actually occur during a normal race.[10] The experts also reviewed the control videos of the skiers doing the same run without injury, which formed part of the basis for their interpretation of the injury videos. However, we often see that skiers make errors in technique or strategy resulting in unbalanced positions similar to those leading to ACL injuries, but still manage to recover without injury. In other words, using 'error-free' runs as controls, it is not possible to discern exactly, the factors that lead to injuries. In the same way, bumps, flat light and difficult snow conditions often occur in the WC, yet injury does not necessarily occur. Direct evidence of causation would require a comparison to 'near-injury' situations, but it is not possible to obtain a systematic sample of such videos. Nevertheless, identifying the factors that seem to play a part in the occurrence of injury is an important step to generate hypotheses and ideas for injury prevention.[4 11 12]

Skier technique and strategy

Factors related to the skier technique and strategy were markedly different between each of the injury mechanisms, that is, the slip-catch, the landing back-weighted and the dynamic snowplow. This was somewhat expected, as the skiing situation differs markedly between the three mechanisms.[5] However, it is interesting to note that, across mechanisms, the experts point to the skiers' mistakes as the key factors leading to the injury situations. In all cases, the racer came out of balance backwards and/or inwards, mainly due to inappropriate technique and strategy. Stable technique and good tactical decisions require a high level of fitness, good risk management and experience as a racer. An interesting question is whether the skier technique and strategy, and therefore injury risk, is influenced by fitness level, risk taking behaviour and racing experience.

It seems reasonable that improved fitness would improve skiing technique and thus increase skiing safety. However, as the best racers are extremely fit, this factor is mainly relevant for the younger and novice WC racers. Studies have shown that specific neuromuscular training programs reduce the risk of non-contact ACL injury in team sports like handball and football.[13] Whether similar training programs could help alpine skiers, has not been tested. While improving knee control in vulnerable situations is one option, another would be to train ski racers to recognise the risk situations and, if possible, avoid these altogether or respond by 'bailing out' in time.

Race conditions

Regarding race conditions, small bumps on the course were reported as a main contributor. In eight of the 10 slip-catch cases, bumpy conditions were assumed to contribute towards an unbalanced position and/or catching the edge. Nevertheless, it may be questioned whether a smoother snow surface would increase skiing safety. It is suggested that a very smooth surface may lead to a strong ski-snow interaction over the whole length of the ski, so that energy cannot be released without being transmitted to the body.[14] In addition, both aggressive snow and icy conditions were assumed to contribute in half of the slip-catch cases, each. However, it is suggested that the most risky situation is when the snow conditions are inconsistent throughout the course.[14] The equipment must be tuned for the iciest part, and the skis then react too fast when going from icy conditions to more aggressive snow.

Course difficulties, such as challenging course/piste, jumps and course setting were also reported as contributing risk factors. The obvious solution would be to make courses less challenging, but it is not known if there are fewer injuries on easy courses. Certainly, a more difficult course requires the athlete to manage risk well. To that end, more jump testing and more training runs prior to the race could be helpful. In general, we know that the injury risk is highest in downhill followed by super-G and giant slalom and lowest in slalom, but we do not know whether this is directly related to the characteristics of the different disciplines, such as course difficulties and speed.[1] Reduced speed will obviously decrease the energy involved during a fall/crash and thereby reduce the risk. However, we know that most of the ACL injuries occur before or without falling. Thus, we do not know to what extent reduced speed can decrease the risk of ACL injuries, although it would give more time to the athlete to react, adapt to and recover from an out of balance position.

Equipment

According to the experts, the main equipment-related contributor to the injury situations was a too aggressive skis and/or boots. Our results show that prior to almost all the ACL injury situations, the racer was out of balance backwards and/or inwards. When the skier is out of balance, he/she is unable to control the carving of the ski, and it seems reasonable to assume that an aggressive skis may more easily "catch the edge". The boots used by the athletes today allow a high direct force transmission from the skis to the body due to the tightness and stiff plastic material. When the skier lands on the ski tails after jumping, it has been assumed that an ACL injury may occur due to the stiff boot cuff, which creates an anterior drawer of the tibia relative to the femur.[6] It has been suggested that less aggressive boots, for example, less cuff stiffness, may decrease the ACL strain and risk of injury during a landing back-weighted situation.[15] In addition to aggressive skis and boots, incorrect setup may affect the athlete's position over the skis and the natural knee kinematics, leading to an increase in the risk of the ACL injury.[16]

CONCLUSION

We have described the skiing situation leading to ACL injuries in the WC alpine skiing and identified the factors related to the skier technique, skier strategy and the specific race conditions as the main contributors to the injury situations. Skier errors, mainly technical mistakes and inappropriate tactical choices, were the dominant factors.

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Competing interests None.

Ethical approval The study was reviewed by the Regional Committee for Medical Research Ethics, South-Eastern Norway Regional Health Authority, Norway.

Provenance and peer review Not commissioned; externally peer reviewed.

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