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Mechanisms of Anterior Cruciate Ligament Injury in World Cup Alpine Skiing

A Systematic Video Analysis of 20 Cases

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Background: There is limited insight into the mechanisms of anterior cruciate ligament injuries in alpine skiing, particularly among professional ski racers.

Purpose: This study was undertaken to qualitatively describe the mechanisms of anterior cruciate ligament injury in World Cup alpine skiing.

Study Design: Case series; Level of evidence, 4.

Methods: Twenty cases of anterior cruciate ligament injuries reported through the International Ski Federation Injury Surveillance System for 3 consecutive World Cup seasons (2006-2009) were obtained on video. Seven international experts in the field of skiing biomechanics and sports medicine related to alpine skiing performed visual analyses of each case to describe the injury mechanisms in detail (skiing situation, skier behavior, biomechanical characteristics).

Results: Three main categories of injury mechanisms were identified: slip-catch, landing back-weighted, and dynamic snowplow. The slip-catch mechanism accounted for half of the cases (n = 10), and all these injuries occurred during turning, without or before falling. The skier lost pressure on the outer ski, and while extending the outer knee to regain grip, the inside edge of the outer ski caught abruptly in the snow, forcing the knee into internal rotation and valgus. The same loading pattern was observed for the dynamic snowplow (n = 3). The landing back-weighted category included cases (n = 4) where the skier was out of balance backward in flight after a jump and landed on the ski tails with nearly extended knees. The suggested loading mechanism was a combination of tibiofemoral compression, boot-induced anterior drawer, and quadriceps anterior drawer.

Conclusion: Based on this video analysis of 20 injury situations, the main mechanism of anterior cruciate ligament injury in World Cup alpine skiing appeared to be a slip-catch situation where the outer ski catches the inside edge, forcing the outer knee into internal rotation and valgus. A similar loading pattern was observed for the dynamic snowplow. Injury prevention efforts should focus on the slip-catch mechanism and the dynamic snowplow.

Keywords: anterior cruciate ligament (ACL) injury; injury mechanism; alpine skiing; professional ski racer; video analysis

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Recent data from the International Ski Federation (FIS) Injury Surveillance System (ISS) have documented that the risk of injury in World Cup (WC) alpine skiing is high.[13-15] During the 5-month FIS WC season, 1 in every 3 skiers sustains a time-loss injury,[14] and in competition the incidence rate is 9.8 injuries per 1000 runs.[13] Similar to recreational skiers,[20,23,25] the most common problem in professional skiers is knee injuries, and the most frequent specific diagnosis is a complete rupture of the anterior cruciate ligament (ACL).[13] The high proportion of ACL injuries among recreational skiers[40,51] and professional ski racers[44,48,50] is described by previous studies.

Understanding the mechanism for such injuries is essential to their prevention.[1,36,49] However, our knowledge of how ACL injuries occur is limited,[8,9,19,22,24] particularly among professional ski racers. The boot-induced anterior drawer (BIAD) and the phantom foot mechanisms were suggested based on qualitative video analysis of 10 ACL injuries, mainly among recreational skiers.[10] The BIAD occurs when a skier loses balance backward when jumping and lands on the ski tails with extended knees. As the tails impact the snow surface, loads are transmitted through the skis, bindings, and rigid boots to the skier, resulting in an anterior drawer of the tibia relative to the femur and potentially sufficient strain to injure the ACL. It has also been suggested that the BIAD mechanism may occur in combination with a powerful contraction of

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the quadriceps muscles during a backward fall among professional ski racers.[17,35]

The phantom foot is claimed to be the most common mechanism for ACL injuries in recreational skiing.[10,40] In this situation, the skier is out of balance backward with the hips below the knees. The uphill arm is back, and the upper body generally faces the downhill ski. The injury occurs when the inside edge of the downhill ski tail engages the snow surface, forcing the knee into internal rotation in a deeply flexed position. The ski acts as a lever to twist or bend the knee, hence the term "phantom foot." Internal rotation of the knee was also suggested to be a key factor in an ACL injury suffered by a WC downhill skier based on a 3-dimensional kinematic reconstruction.[31] In this case, the skier lost grip of his right ski, causing him to go into a wide sprawling position before the edge of his left ski caught the snow surface, forcing the left knee into internal rotation and valgus.

Video of actual injuries contain important information on what took place when the injury occurred. The analyses of injury video recordings have provided detailed descriptions of noncontact ACL injury mechanisms in team sports.[26,30,43] This information, in turn, has formed the basis for exercise-based prevention programs with documented effect.[39,42] Based on the same principles,[1,27] the aim of this study was to describe the injury situations and mechanisms of ACL injuries among WC alpine skiers based on systematic analysis of video recordings.

MATERIALS AND METHODS

Injury and Video Recording

We obtained video recordings of injuries reported through the FIS ISS for 3 consecutive WC seasons (2006-2009). The FIS ISS injury registration was based on interviews with all athletes, coaches, and medical staff from 10 of the largest WC teams.[13-15] In total, 281 injuries were reported among WC alpine skiers during this time period, 209 of these occurring during WC and World Ski Championship (WSC) events (Figure 1). Of these, 21 knee injuries were reported—and later confirmed with team medical staff—as total ACL tears. The majority of ACL injuries occurred during competition (n = 18), with the remaining sustained during official training (n = 3).

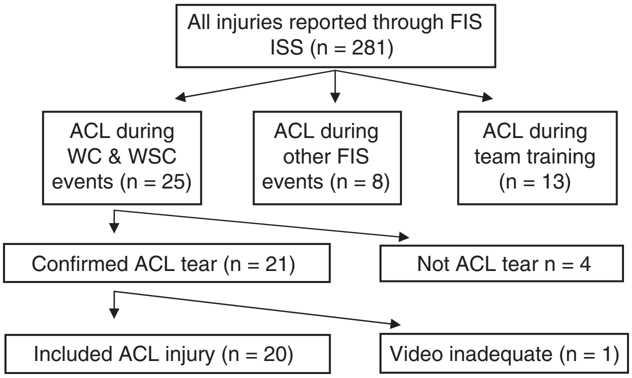

Figure 1. Flowchart showing the process to identify videos of anterior cruciate ligament injuries in World Cup alpine skiing based on injury registration through the International Ski Federation Injury Surveillance System (2006-2009).

The television producer, Infront (Italy), provided video footage of the entire run for each of the confirmed ACL injuries during competition. Additional footage of injuries from official training and WSC were obtained directly from FIS or 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 1 camera angle, 6 injuries from 2 camera angles, and 4 injuries from 3 camera angles.

Infront also provided footage of runs by noninjured matched skiers to compare injury to noninjury situations in competition. We selected matched controls from the same race and the same run among skiers who had been interviewed through the FIS ISS with no injury, with starting numbers as close as possible to the injured skier's. We selected 2 athletes who completed the run for each of the 15 injury cases from WC competition. In total, 19 of the 30 runs by matched controls were useful, as some footage did not cover the entire run and were excluded.

Video Processing

We received 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), we edited 2 versions of each run, 1 full version showing the entire run and 1 short version showing the specific injury situation (including a few gates before the injury situation and until the skier came to a full stop). Analog files were converted to

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digital video files in 4:3 format (Episode Engine Admin, version 5.0, Apple) with a DV 25 PAL codec. All files were converted to QuickTime (.mov) files, which enabled us to analyze the files using QuickTime Player (version 7, Apple). In addition, we produced deinterlaced short versions covering the assumed time of injury, which increased the effective frame rate from 25 to 50 Hz using Adobe Photoshop (version CS, Adobe System Inc, San Jose, California). In 2 cases, deinterlacing was not useful.

Ethical Approval

The study was reviewed by the regional committee for medical research ethics, South-Eastern Norway Regional Health Authority, Norway, and approved by the Norwegian Social Science Data Services.

Video Analysis

We invited 7 international experts in the field of skiing biomechanics and sports medicine related to alpine skiing to form an analysis team. Four are biomechanists (T.K., E.M., V.S., R.R.) and 3 are orthopaedic surgeons (H.K., L.N., C.I.). The analysis process was organized into 2 parts. The first part consisted of a 1-day meeting where the experts independently identified the time of ACL rupture on the videos, referred to as the index frame. During this phase, the experts were blinded to the opinion of the other analysts, but they were provided with information registered through the FIS ISS for each case. This information included sex, injured side, and discipline (downhill, super-G, giant slalom, and slalom). After the individual analysis, the cases were reviewed in a group session to reach a consensus on the index frame. In 4 cases, there was more than 1 plausible injury time point, typically during the crash after the first incident where the skier lost control. In these cases, the group also agreed on alternative index frames for the subsequent incidents.

After identifying the injury time point, the experts independently analyzed the mechanisms for each case, including the alternative index frames, using an analysis form developed during a pilot project. The form included closed and open questions concerning (1) the circumstances of injury, (2) the skiing situation, (3) skier behavior, and (4) joint angles and limb positions (see Appendix 1, available in the online version of this article at http://ajs.sagepub.com/supplemental/). We also asked the experts to review the control runs carefully to aid in their interpretation of the injury cases. To complete the forms, we encouraged them to use the deinterlaced sequences and the frame-by-frame function. Additionally, the analysts were provided still pictures of the index frame.

Part 2 of the analysis consisted of a 3-day consensus meeting where the experts carefully reviewed each case based on the completed forms. Each video was examined as many times as needed to obtain a consensus decision for all categorical variables. To obtain a consensus decision for the categorical variables, at least 4 of the 7 experts had to agree. If fewer than 4 experts agreed, the variable was reported as "no consensus."

Statistical Analysis

Flexion angles of the knee and hip joints are reported as the median of the individual estimates, along with the mean absolute deviation from the median. As a measure of the accuracy of the index frame estimates, we reported the mean absolute deviation (in milliseconds) of the initial, individual estimates from the index frame determined in the consensus meeting.

RESULTS

ACL Injury Cases

One of the 21 injury cases had to be excluded, as the lower extremity was fully occluded by the terrain on the video when the injury happened. The characteristics of the 20 analyzed ACL injury cases, 13 among males and 7 among females, are shown in Appendix 2 (available in the online version of this article at http://ajs.sagepub.com/supplemental/). There were 11 injuries to the right knee and 9 to the left knee. Most injuries were in the downhill discipline (n = 10), followed by giant slalom (n = 7), slalom (n = 2), and super-G (n = 1).

Weather and Snow Conditions

The weather conditions were categorized as clear in 18 cases and foggy in 2. The visibility was assumed to be reduced in 10 cases (mainly because of flat light), good in 9, and was not possible to judge in 1 case. The snow conditions were categorized as hard in 15 cases, soft in 2 (because of loose snow on the top of a hard surface), and not possible to judge in 3 cases. The piste conditions were smooth in 15 cases, rough/bumpy in 4, and not possible to judge in 1 case.

Skiing Situation

Nineteen of the 20 analyzed injuries occurred during skiing, only 1 during a crash. In more than half of the cases (n = 12), the skier was turning at the time of injury. In all of these cases, the skier was out of balance backward and/or inward, mainly during the steering phase out of the fall line. The second most common skiing situation (n = 4) at the time of injury was landing back-weighted after jumping. In 2 other cases, the skier was traversing and was out of balance backward and/or to the side. In the remaining 2 cases, 1 skier hooked the gate in a balanced position, and another skier was tumbling after having lost control. In 17 of the 20 cases, there was no binding release on the injured side. In the remaining 3 cases, the binding released well after the identified time of injury (Appendix 2; available online).

Skier Behavior, Knee Motion, and Knee Loading Patterns

Based on the video analysis, injury mechanisms were classified into 3 main categories named the slip-catch, landing

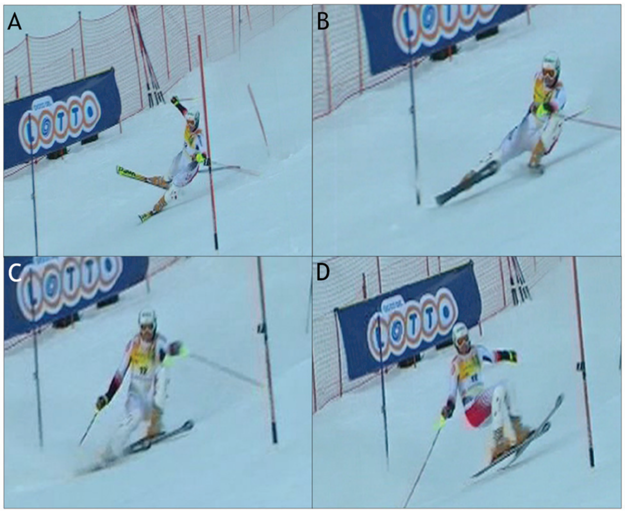

Figure 2. Injury 1: slip-catch (right knee). A (−400 ms), the skier is out of balance backward and inward in the steering phase out of the fall line. B (−120 ms), as the skier tries to regain snow contact with the unweighted outer ski, he extends his right knee. C (index frame), the outer ski catches the inside edge abruptly, forcing the right knee into valgus and internal rotation. D (+200 ms), the skier falls backward to his right.

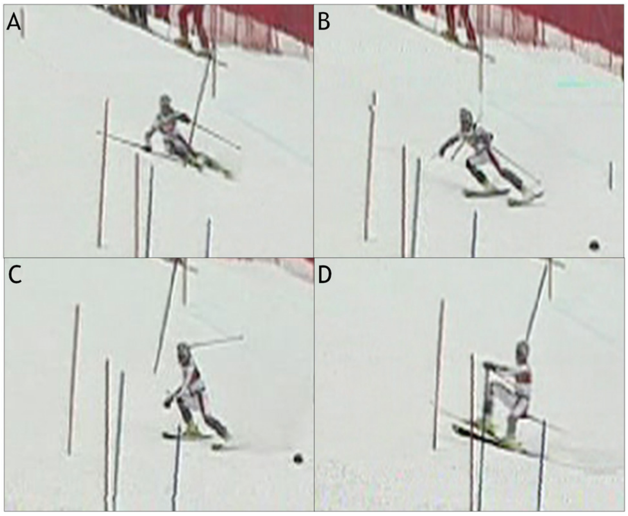

Figure 3. Injury 2: Slip-catch (left knee). A (−580 ms), the skier is out of balance inward and drifting into the steering phase out of the fall line. B (−280 ms), as the skier tries to regain grip on the outer ski, he extends his left knee. C (index frame), the outer ski catches the inside edge, forcing the left knee into valgus and internal rotation. D (+320 ms), the skier falls backward.

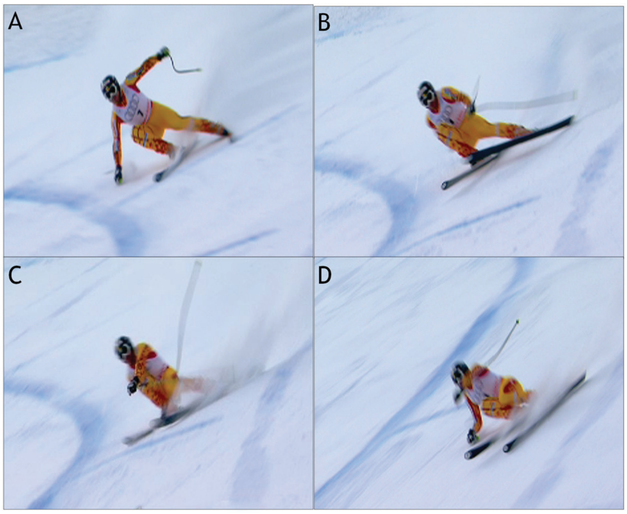

Figure 4. Injury 8: Slip-catch (left knee). A (−320 ms), the skier is out of balance backward and inward in the steering phase into the fall line. B (−120 ms), the outer ski skids away from the body's center of mass, and as the skier tries to regain grip with the outer ski, he extends his left knee. C (index frame), due to a small bump, the outer ski catches the inside edge abruptly, forcing the left knee into valgus and internal rotation. D (+480 ms), the skier falls inward to his right.

back-weighted, and dynamic snowplow (Appendix 2, available online). The slip-catch mechanism accounted for half of the cases (n = 10, cases #1-10). These were characterized by a common pattern where the skier was turning and out of balance backward and/or inward. The skier lost pressure on the outer ski, which then drifted away from the body's center of mass. The skier extended the leg, attempting to reestablish grip with the outer ski. The outer ski then abruptly caught the snow surface, forcing the nearly straight knee into flexion, internal rotation, and valgus at the time of injury. A detailed description of 3 of these cases is shown in Figures 2 through 4 (see the video supplement, available in the online version of this article).

Landing from a jump out of balance backward was another primary mechanism (n = 4, cases #11-14). All 4 injuries in this category occurred in the downhill discipline. During the flight phase of the jump, the skier lost balance backward and, as a result, landed on the ski tails with a large clap angle[2] and nearly extended knees. As the tail of the ski was loaded, the skis rotated forward, and the skier attempted to recover his balance. The suggested loading mechanism was a combination of tibiofemoral compression[37] and anterior drawer of the tibia related to the femur. A detailed description of 2 of these cases is shown in Figures 5 and 6 (see the video supplement, available online).

The third category of injury mechanisms was referred to as the "dynamic snowplow" (n = 3, cases #15-17). All 3 of these cases occurred in the downhill discipline—2 in the traversing section of the course and 1 in a left hand turn. The skier was out of balance backward with more weight on 1 ski than the other. The unweighted ski then drifted away from the body's center of mass, forcing the skier into a split position. The loaded ski then rolled from the outside edge to the inside edge, which subsequently

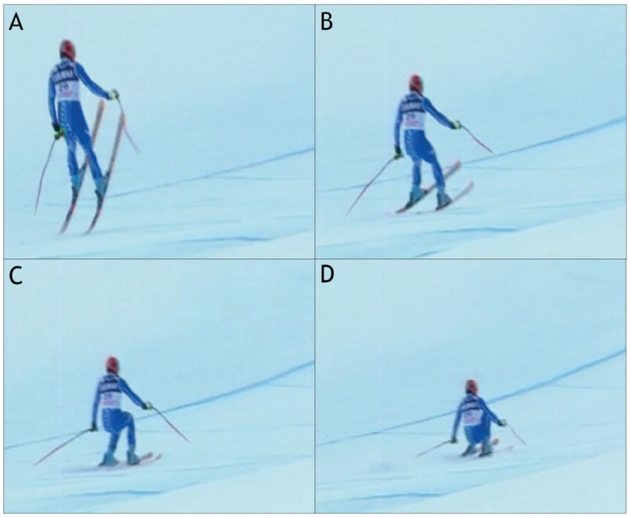

Figure 5. Injury 11: Landing back-weighted after jumping (left knee). A (−420 ms), the skier is out of balance backward and lands on the ski tails with a large clap angle. B (−160 ms), the right ski hits the snow surface slightly before the left ski. C (index frame), the skier tries to recover from a backward-leaning position. D (+240 ms), the skier falls backward, to the left.

engaged the snow surface and forced the knee into internal rotation and/or valgus. The positioning of the skis at the time of injury was similar to a snowplow, hence the term "dynamic snowplow." A description of 1 of these cases is shown in Figure 7 (see the video supplement, available online).

The remaining 3 cases, all from giant slalom, represented mechanisms distinctly different from the categories described above. The first case happened during turning, as the outside edge on the inner ski engaged the snow surface, forcing the knee into external rotation in a deeply flexed position (case #18). The second case resulted from hooking a gate with the inner ski, forcing the knee into external rotation and valgus (case #19). The final case occurred during a crash, where the injury was assumed to result from forceful hyperextension of the knee as the ski tail hit a safety net (case #20).

DISCUSSION

This is the first study to describe the mechanisms of ACL injuries among professional ski racers based on systematic video analyses. Most of the injuries occurred while the athlete was still skiing, and we identified 3 distinctive mechanisms: the slip-catch, landing back-weighted, and the dynamic snowplow. The slip-catch mechanism has not been described previously, and both the slip-catch and the dynamic snowplow mechanisms are markedly different from the mechanisms described among recreational

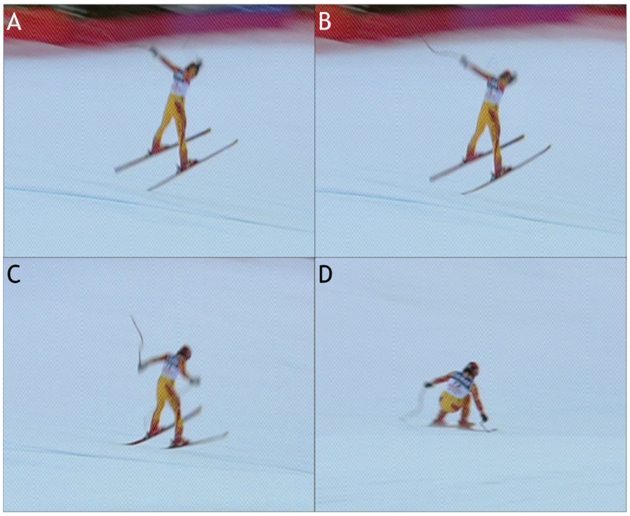

Figure 6. Injury 13: Landing back-weighted after jump (right knee). A (−120 ms), the skier is out of balance backward in flight. B (−80 ms), he lands on the ski tails with a large clap angle. C (index frame), the weight is mainly on the right ski, with a slightly flexed knee. D (+260 ms), the skier falls backward to the right.

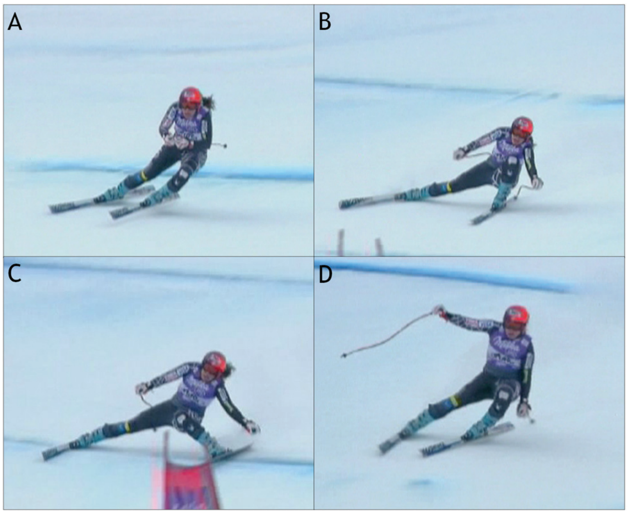

Figure 7. Injury 15: Dynamic snowplow (left knee). A (−620 ms), because of a small bump, the skier loses ground contact with the inner ski. She gets out of balance backward and inward. B (−240 ms), the right ski drifts away from the body's center of mass, while the inner ski rolls from the outside edge to the inside edge. C (index frame), the inside edge on the inner ski engages the snow surface, forcing the left knee into valgus and internal rotation. D (+540 ms), the skier regains balance from a snowplow position and eventually makes a complete stop.

skiers.[10,24,40] This is not unexpected, as professional ski racing requires extreme skiing skills, experience, and fitness,[3,52] as well as more aggressive equipment.[21] The skiing conditions and the terrain are also obviously more challenging.

Internal Rotation and Valgus Loading

An interesting feature of the slip-catch and dynamic snowplow mechanisms is that the end result—most likely internal rotation and valgus loading of the knee—appeared to be very similar in both cases. In the slip-catch mechanism, which accounted for half of the cases (n = 10), the skiers were reaching with their outer ski (therefore extending their knee) to reestablish snow contact. Then the inside edge abruptly caught the snow surface, forcing the knee into internal rotation and valgus. This loading pattern is related to the carving ski's self-steering effect. When the edge of the ski catches the snow surface, the ski acts as a lever to internally rotate the knee. We identified the same knee loading pattern for the dynamic snowplow mechanism. In these cases (n = 3), the ski again drifted away from the body's center of mass, causing the skier to go into a split position. While the weighted ski rolled from the outside to the inside edge, which engaged the snow surface, the knee was forced into internal rotation and/or valgus. This mechanism corresponds very well to the "wide snowplow" mechanism described by Krosshaug et al,[31] based on a 3-dimensional motion reconstruction of an ACL injury suffered by a WC downhill skier. In total, 13 of the 20 cases included in this study occurred because of internal rotation and/or valgus loading.

Phantom foot, the mechanism claimed to be the most common cause of ACL injuries in recreational skiing, also involves internal rotation as one of the main components.[10] This occurs when the inside edge of the downhill ski tail engages the snow surface while the skier is in a deeply flexed, backward-leaning position. Taking this observation and the results of the current investigation into account, it seems likely that internal rotation is a key component for ACL injury in alpine skiing.

This is supported by findings from in vitro and in vivo studies.[12,18,32,33,38] Hame et al[18] investigated the strain generated in the ACL with application of tibial torque at different knee flexion angles in a cadaveric study. They reported that internal tibial torque applied to either a fully extended or fully flexed knee represents the most dangerous loading conditions for injury from twisting falls during skiing. Mizuno et al[38] recently developed a computer-simulated model for estimation of ACL strain in complex 3-dimensional loading conditions, reporting that the most prominent predictors for ACL strain were anterior shear force, valgus torque, and internal rotation torque. The loads also varied as a function of knee flexion angle, with the highest ACL strain occurring between 0° and 20° of knee flexion.

Studies based on qualitative video analysis of noncontact ACL injuries in ball/team sports agree that valgus loading seems be an important component of the injury mechanism.[4,6,30,43] They also agree that the knee is relatively straight at the time of injury, which typically occurs in cutting and landing situations. To obtain more precise estimates of knee kinematics in real ACL injury situations, a model-based image-matching technique was developed by Krosshaug and Bahr[28] to reconstruct injury mechanisms from uncalibrated video sequences. The first study using this method to quantify knee kinematics in a series of 10 injuries in team handball and basketball recently reported that valgus motion in combination with internal rotation appears to be a main component of the injury mechanism.[26] This motion seems to occur approximately 40 milliseconds after initial contact with the playing surface on a slightly flexed knee. Their hypothesis is that internal rotation and anterior tibial translation are a result of valgus loading, which makes compressive loading on the lateral joint component, because of the joint surface geometry.

A combination of both internal rotation and valgus loading was observed in the majority of cases in the current study. This finding corresponds well to the results of Koga et al,[26] which emphasized valgus coupled with internal rotation as a main component in ACL injury mechanism. The degree to which tibiofemoral compressive load and quadriceps contraction contribute to ACL injury in slip-catch situations is not possible to judge from the videos in this study. However, in most cases the knee was forcefully flexed when the ski caught the edge, closely resembling the motion pattern observed for landing and cutting injuries in team handball and basketball.[26]

Binding Release

We observed no binding release in 12 of the 13 cases involving internal rotation and/or valgus, and in the remaining case the binding released well after the time of injury. The same pattern was seen for the other mechanisms. The ski boot binding system has 2 functions: release and retention. The release function is designed to release the ski from the boot under circumstances where the ski may act as a lever to potentially injure the lower leg through twisting or bending. The retention function is designed to provide a rigid coupling between the boot and the ski, thus allowing the skier to exert forces to the ski. Current binding systems are also designed to release in response to a lateral force applied to the front of the ski, an upward force at the heel and a backward lean (upward release at the toe).[47] Since the mechanisms of ACL injury have been unknown, it has not been possible to determine the appropriate release criteria for bindings.[7,41] Based on the data from the current study, it will be a difficult task to design a binding system that can differentiate between adverse internal rotation and valgus loading and aggressive, but normal, skiing turns on the other hand.

Anterior Tibial Drawer

In the category identified as landing back-weighted (n = 4), the skier landed with nearly extended knees on the ski tails after a jump. This appeared quite similar to the BIAD mechanism described in recreational skiing. However, we elected to refer to this category as landing back-weighted as there may be several loading conditions that can contribute to ACL injury, not just an anterior tibial drawer caused by the back spoiler of the boot. According to previous theories, an ACL injury may occur during the clapping period right after initial contact attributable to the BIAD and tibiofemoral compression load.[10,53] Another suggested loading condition that may generate anterior tibial drawer in this situation is improper muscle activation of quadriceps and hamstrings. This theory is based on electromyography and kinematics of an accidental ACL injury suffered by a professional racer under experimental conditions (including a reference group).[2]

Previous studies have also reported that an ACL injury may occur during the recovery period from a backward-leaning position after an uncontrolled landing. It has been suggested that ACL loading in this period is caused by an eccentric quadriceps contraction in combination with the BIAD,[5,16,17] and that this can only occur among skiers who have strong enough quadriceps and are skilled enough to recover from the compromised falling-back position.[35] However, the literature regarding quadriceps contribution to ACL failure is controversial.[16,34,54] Moreover, studies have reported that a falling-back position after an uncontrolled landing may cause hyperflexion of the knee and potentially sufficient strain to injure the ACL.[8,18] Based on our video analysis, it is not possible to determine which of these theories are more likely, as we cannot be sure of the exact moment of injury.

Another interesting observation was that in 2 of the 4 landing back-weighted cases, internal rotation and valgus loading was suggested to contribute as well. This has also been reported in a previous case study where a former WC skier sustained an isolated ACL injury in a situation characterized by a massive quadriceps contraction to prevent a backward fall, combined with an internal rotation of the knee.[17]

Methodologic Considerations

This is the first study employing systematic, qualitative video analysis to describe ACL injury mechanisms among professional ski racers. By utilizing video recordings, it is possible to describe the injury mechanisms of real injury situations in more detail than retrospective interviews.[11,35,45] Interviews may be influenced by recall bias or simply the fact that these injuries happen at such high speed that the athlete may not even be able to describe what took place.[27] However, there are some limitations to this method of which one should be aware.[26,29]

First, we cannot in all cases be sure of the exact moment of injury. Nevertheless, as shown in Appendix 2 (available online), the individual estimates of the index frame were remarkably consistent in most cases. In some cases, the initial estimates were less consistent with several different initial opinions about when the injury occurred before the consensus meeting. In 4 cases, there was more than 1 plausible injury time point. These were also analyzed (see Appendix 2). However, the alternative injury situations appear less likely than primary injury moments, and in each case we have used the first plausible injury situation as the basis for our main conclusions. Also, we cannot be sure whether our observations of joint angles and body motions are, in fact, the mechanisms leading to the ACL injury and not a result of the injury.

Visual analysis of injury mechanisms is a convincing exercise, where remarkably consistent patterns can often be readily identified. However, it has also been documented that qualitative video analysis is not ideal for estimating joint kinematics. A validation study reported an underestimation of knee and hip flexion, as well as poor consistency between experts.[29] As seen in Appendix 2, our joint angle estimates also varied substantially in some cases, particularly if it were difficult to visualize the hip and knee. To increase measurement accuracy, we strived to obtain the best possible video quality through video processing. Nevertheless, the description of joint kinematics reported in this study should be interpreted with caution.

Further Perspectives

In this investigation, we have identified 3 categories of ACL injury mechanisms and described characteristics common to each. To describe knee kinematics at the time of injury more accurately, a more sophisticated method such as the model-based image-matching technique[26] would be required. For this, 2 or 3 camera views where the injured knee is shown clearly from different perspectives are needed. In addition, to fully understand the mechanisms of the ACL injuries, a description of the events leading up to the injury situations should be included. We observed that in 19 of the 20 analyzed cases, the skier was out of balance backward and/or inward at the time of injury. Identifying the most critical factors that contribute to this out-of-balance situation could also provide clues to prevent these injuries.

We found that most of the injuries occurred in a slip-catch situation while the athlete was still skiing, without or before falling. This injury situation develops rapidly because of high skiing speeds. With aggressively carving skis and aggressive snow conditions, large forces are generated when the inside edge catches the snow surface. Although there is probably no single solution that will prevent ACL injuries from occurring, risk may be reduced from a combination of measures that can reduce the energy involved in a potential injury situation and give the skier more time to react and adjust. Factors that need to be considered include the equipment (the ski-plate-binding-boot system), snow conditions (especially changing snow conditions from injected to less aggressive snow), course setting and speed, and athlete preparation and conditioning.

It may be possible to train skiers to recognize potential injury situations to either avoid these altogether or to respond by “bailing out” in time. After identifying the phantom foot mechanism in recreational alpine skiing, Ettlinger et al[10] developed an awareness training program that reduced the injury risk among ski patrols and instructors by 62%. The program focused on improving psychomotor skills to develop an awareness of the events leading to ACL injury. In addition, studies have shown that a specific injury prevention program, including neuromuscular training, reduced the risk of ACL injury significantly among athletes in handball and football.[39,46]

CONCLUSION

We identified 3 distinctive mechanisms of ACL injuries that we have termed the slip-catch, landing back-weighted, and the dynamic snowplow. The slip-catch mechanism has not been described previously, and both the slip-catch and dynamic snowplow are markedly different from the mechanisms described in recreational skiing, characterized by internal rotation and valgus loading of the knee when the inside edge of the ski abruptly engages the snow surface.

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REFERENCES

1. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med*. 2005;39:324-329.
2. Barone M, Senner V, Schaff P. ACL injury mechanism in alpine skiing: analysis of an accidental ACL rupture. In: Johnson RJ, ed: *Skiing Trauma and Safety*. 12th vol, ASTM STP 1345. West Conshohocken, PA: American Society for Testing and Materials; 1999:63-81.
3. Bianco T, Malo S, Orlick T. Sport injury and illness: elite skiers describe their experiences. *Res Q Exerc Sport*. 1999;70:157-169.
4. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23:573-578.
5. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32:477-483.
6. Ebstrup JF, Bojsen-Moller F. Anterior cruciate ligament injury in indoor ball games. *Scand J Med Sci Sports*. 2000;10:114-116.
7. Ekeland A, Nordsletten L. Equipment related injuries in skiing: recommendations. *Sports Med*. 1994;17:283-287.
8. Ekeland A, Thoresen BO. Isolated rupture of the anterior cruciate ligament by knee hyperflexion. In: Mote CD Jr, Johnson RJ, eds. *Skiing Trauma and Safety: Sixth International Symposium*. ASTM STP 938. Philadelphia, PA: American Society for Testing and Materials; 1987:61-67.
9. Elmqvist LG Jr. Prevention of cruciate ligament injuries. In: Feagin JA, ed. *The Cruciate Ligaments: Diagnosis and Treatment of Ligamentous Injuries About the Knee*. 2nd ed. New York, NY: Churchill Livingstone; 1994:495-505.
10. Ettlinger CF, Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med*. 1995;23:531-537.
11. Fischer JF, Leyvraz PF, Bally A. A skiing dynamic analysis of knee ligament injuries in alpine skiing. *Acta Orthop Belg*. 1994;60:194-203.
12. Fleming BC, Renstrom PA, Beynnon BD, et al. The effect of weightbearing and external loading on anterior cruciate ligament strain. *J Biomech*. 2001;34:163-170.
13. Flørenes TW, Bere T, Nordsletten L, Heir S, Bahr R. Injuries among male and female World Cup alpine skiers. *Br J Sports Med*. 2009;43:973-978.
14. Flørenes TW, Nordsletten L, Heir S, Bahr R. Injuries among World Cup ski and snowboard athletes. *Scand J Med Sci Sports*. 2010 Jun 18; [Epub ahead of print].
15. Flørenes TW, Nordsletten L, Heir S, Bahr R. Recording injuries among World Cup skiers and snowboarders: a methodological study. *Scand J Med Sci Sports*. 2009 Dec 18; [Epub ahead of print].
16. Gerritsen KG, Nachbauer W, van den Bogert AJ. Computer simulation of landing movement in downhill skiing: anterior cruciate ligament injuries. *J Biomech*. 1996;29:845-854.
17. Geyer M, Wirth CJ. A new mechanism of injury of the anterior cruciate ligament [in German]. *Unfallchirurg*. 1991;94:69-72.
18. Hame SL, Oakes DA, Markolf KL. Injury to the anterior cruciate ligament during alpine skiing: a biomechanical analysis of tibial torque and knee flexion angle. *Am J Sports Med*. 2002;30:537-540.
19. Howe J, Johnson RJ. Knee injuries in skiing. *Clin Sports Med*. 1982;1:277-288.
20. Hunter RE. Skiing injuries. *Am J Sports Med*. 1999;27:381-389.
21. International Ski Federation. FIS Masters Rules Specifications for competition equipment and commercial markings. Edition 2009/10 (valid from the season 2009/10). Available at http://www.fis-ski.com/data/document/edition2009_nov.pdf. November 30, 2009. Accessed March 8, 2011.
22. Jarvinen M, Natri A, Laurila S, Kannus P. Mechanisms of anterior cruciate ligament ruptures in skiing. *Knee Surg Sports Traumatol Arthrosc*. 1994;2:224-228.
23. Johnson RJ, Ettlinger CF. Alpine ski injuries: changes through the years. *Clin Sports Med*. 1982;1:181-197.
24. Kennedy JC, Weinberg HW, Wilson AS. The anatomy and function of the anterior cruciate ligament: as determined by clinical and morphological studies. *J Bone Joint Surg Am*. 1974;56:223-235.
25. Koehle MS, Lloyd-Smith R, Taunton JE. Alpine ski injuries and their prevention. *Sports Med*. 2002;32:785-793.
26. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218-2225.
27. Krosshaug T, Andersen TE, Olsen OE, Myklebust G, Bahr R. Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities. *Br J Sports Med*. 2005;39:330-339.
28. Krosshaug T, Bahr R. A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. *J Biomech*. 2005;38:919-929.
29. Krosshaug T, Nakamae A, Boden B, et al. Estimating 3D joint kinematics from video sequences of running and cutting maneuvers–assessing the accuracy of simple visual inspection. *Gait Posture*. 2007;26:378-385.
30. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35:359-367.
31. Krosshaug T, Slauterbeck JR, Engebretsen L, Bahr R. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scand J Med Sci Sports*. 2007;17:508-519.
32. Markolf KL, Burchfield DM, Shapiro MM, et al. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13:930-935.
33. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament: an in vitro study performed with a new experimental technique. *J Bone Joint Surg Am*. 1990;72:557-567.
34. Markolf KL, O'Neill G, Jackson SR, McAllister DR. Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med*. 2004;32:1144-1149.
35. McConkey JP. Anterior cruciate ligament rupture in skiing: a new mechanism of injury. *Am J Sports Med*. 1986;14:160-164.
36. Meeuwisse WH. What is the Mechanism of No Injury (MONI)? *Clin J Sport Med*. 2009;19:1-2.
37. Meyer EG, Haut RC. Anterior cruciate ligament injury induced by internal tibial torsion or tibiofemoral compression. *J Biomech*. 2008;41:3377-3383.
38. Mizuno K, Andrish JT, van den Bogert AJ, McLean SG. Gender dimorphic ACL strain in response to combined dynamic 3D knee joint loading: implications for ACL injury risk. *Knee*. 2009;16:432-440.

39. Myklebust G, Engebretsen L, Braekken IH, et al. Prevention of noncontact anterior cruciate ligament injuries in elite and adolescent female team handball athletes. *Instr Course Lect*. 2007;56:407-418.
40. Natri A, Beynnon BD, Ettlinger CF, Johnson RJ, Shealy JE. Alpine ski bindings and injuries: current findings. *Sports Med*. 1999;28:35-48.
41. Nordsletten L, Lystad H, Ekeland A. On-slope evaluation of release bindings for world-class alpine racers. *Scand J Med Sci Sports*. 1996;6:176-179.
42. Olsen OE, Myklebust G, Engebretsen L, Holme I, Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ*. 2005;330:449.
43. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32:1002-1012.
44. Pujol N, Blanchi MP, Chambat P. The incidence of anterior cruciate ligament injuries among competitive Alpine skiers: a 25-year investigation. *Am J Sports Med*. 2007;35:1070-1074.
45. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train*. 2008;43:396-408.
46. Soligard T, Myklebust G, Steffen K, et al. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *BMJ*. 2008;337:a2469.
47. St-Onge N, Chevalier Y, Hagemeister N, Van de Putte M, De Guise J. Effect of ski binding parameters on knee biomechanics: a three-dimensional computational study. *Med Sci Sports Exerc*. 2004;36:1218-1225.
48. Stevenson H, Webster J, Johnson R, Beynnon B. Gender differences in knee injury epidemiology among competitive alpine ski racers. *Iowa Orthop J*. 1998;18:64-66.
49. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries: a review of concepts. *Sports Med*. 1992;14:82-99.
50. Viola RW, Steadman JR, Mair SD, Briggs KK, Sterett WI. Anterior cruciate ligament injury incidence among male and female professional alpine skiers. *Am J Sports Med*. 1999;27:792-795.
51. Warme WJ, Feagin JA Jr, King P, Lambert KL, Cunningham RR. Ski injury statistics, 1982 to 1993, Jackson Hole Ski Resort. *Am J Sports Med*. 1995;23:597-600.
52. White AT, Johnson SC. Physiological aspects and injury in elite alpine skiers. *Sports Med*. 1993;15:170-178.
53. Yeow CH, Lee PV, Goh JC. Direct contribution of axial impact compressive load to anterior tibial load during simulated ski landing impact. *J Biomech*. 2010;43:242-247.
54. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med*. 2007;41(Suppl 1):i47-i51.
