A systematic video analysis of 69 injury cases in World Cup alpine skiing

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We have limited insight into how injuries occur in professional ski racing. The aim of this study was to describe the injury situations in World Cup alpine skiing. Injuries reported through the International Ski Federation Injury Surveillance System for three consecutive World Cup seasons (2006–2009) were obtained on video. In total, 69 injuries and 124 runs of matched controls were analysed by five experts to evaluate the skiing situation, skier behavior, as well as piste-related factors. A chi-square test (95% CI, P < 0.05) was used to examine whether there was a difference between course sections regarding where the injury situation occurred. The skier was most frequently turning (n = 55) or landing from a jump (n = 13) at the time of injury. Most of the injuries to the head and upper body (96%) resulted from crashes, while the majority of knee injuries (83%) occurred while the skier was still skiing. Gate contact contributed to 30% of the injuries, while 9% occurred at contact with safety nets/material. Almost half of the injuries (46%) occurred in the final fourth of the course. A particular concern was the high contribution of inappropriate gate contact and the high-energy impacts to the body when crashing.

Studies have reported that, on average, one in three World Cup (WC) alpine skiers sustains an acute injury during a 5-month winter season, and the incidence rate in competition (injuries per 1000 runs) is highest for the downhill discipline (17.2), followed by Super-G (11.0), giant slalom (9.2), and slalom (4.9; Flørenes et al., 2009). In total, more than 30% of the injuries are severe, leading to long-term absence from training and competition (more than 28 days). The most common injuries are to the knee, head, hand/thumb, lower leg, lower back, and shoulder (Flørenes et al., 2009, 2012), which is similar to recreational alpine skiing (Johnson, Ettlinger & Shealy, 1997; Hunter, 1999; Koehle et al., 2002; Sulheim et al., 2011). However, to reduce the risk of injury and improve skiing safety, we need to understand why and how injuries occur and identify factors that contribute to the chain of events putting the skier in a vulnerable situation (van Mechelen et al., 1992; Bahr & Krosshaug, 2005; Meeuwisse, 2009). With the exception of the anterior cruciate ligament (ACL) tears (Bere et al., 2011a, b), we have limited knowledge of how injuries occur in alpine ski racing.

In recreational skiing, retrospective interviews of injured skiers have revealed that head and spine injuries mainly occur as a result of falls or collisions with other skiers or objects on the slope, such as trees and lift towers (Koehle et al., 2002; Ackery et al., 2007). It has been suggested that these situations are caused by poorly groomed slopes, equipment failure, unfavorable weather conditions, overcrowding, skier error or high speed with loss of control (Boden & Prior, 2005). Furthermore, studies have reported that knee injuries primarily occur while falling without or before binding release, where the ski acts as a lever to injure the knee through twisting or bending (Fischer et al., 1994; Ettlinger et al., 1995; Natri et al., 1999; Ruedl et al., 2009, 2011). Injuries to the shoulder are mainly caused by a direct fall on the shoulder/arm, or a situation where the pole is planted in the snow or caught by objects on the slope, causing an anterior dislocation of the glenohumeral joint (the so-called “pole planting” situation) (Kocher et al., 1998; McCall & Safran, 2009). In addition, falling with the pole in the skier’s hand is thought to cause “skier’s thumb,” which is a traumatic hyperabduction and extension of the metacarpophalangeal joint (Boutin & Fritz, 2005; Chuter et al., 2009). It is suggested that this injury occurs because the handle of the ski pole acts as a fulcrum at the thumb base (Engkvist et al., 1982).

We do not know to what extent the injury mechanisms described in recreational skiing appear in professional ski racing, where the athletes ski extremely challenging courses and are required to maneuver through gates
under time pressure. By examining video recordings of real injury situations, it is possible to provide a more accurate and complete description of how injuries occur than from retrospective interviews (Bahr & Kroshaug, 2005; Kroshaug et al., 2005). The aim of this study was therefore to describe the injury situations in WC alpine skiing based on systematic video analysis of real injury situations.

Materials and methods

Injury and video recording

We obtained video recordings of injuries reported through the International Ski Federation (FIS) Injury Surveillance System (ISS) for three consecutive WC seasons (2006–2009). This injury registration was based on interviews with athletes, coaches or medical staff from 10 of the largest WC teams (Flørenes et al., 2009, 2012). The athletes, coaches, and medical staff were asked to recall any acute injury sustained by the athletes, which required medical attention, during the 5-month WC season. The interview was done using a form outlining a week-by-week calendar of the WC season as an aide-mémoire. This was found to be the best method in this setting for reducing recall bias in a methodological study we did comparing three different methods (Flørenes et al., 2011). If an injury was recorded, a specific injury registration form was completed for each injury, including information about body part injured, injury circumstances, injury type, injury severity (expressed as days of absence from full participating in training and competition), injured side, and a specific diagnosis (based on team medical staff assessment). This injury registration method has been described previously (Flørenes et al., 2009). In addition to the injury registration based on interviews, we included injuries reported by the technical delegates at WC events during this time period (Flørenes et al., 2011). In total, 178 injuries were reported to occur during WC events, including official training. Of these, there were 136 time-loss injuries, leading to an absence from training and competition of at least 1 day.

The television producer, Infront Sports & Media (Zug, Switzerland), provided video footage of the entire run for each of the time-loss injuries in WC competition (n = 94). They also provided footage of runs by uninjured matched skiers (n = 192) in order to compare injury and no-injury situations. 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 before and after the injured skiers. We selected two to four controls among athletes who did not complete the run for each of the injury cases.

We had to exclude 25 of the 94 injury cases because the injury situation could not be seen well enough on the video. Thus, 69 injury situations were included for the analyses, as well as the matched controls to these injuries (n = 124). In total, 50 injuries were captured from one camera angle, 16 injuries from two camera angles, and three injuries from three camera angles.

Video processing

We received video footage as analog video files on Beta SP (Sony Corporation, Tokyo, Japan). 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). The videotapes were digitized to QuickTime (.mov) files in 4:3 format (Episode Engine Admin, version 5.0, Apple) with a DV 25 PAL codec to preserve the picture quality and to allow for easy frame-by-frame navigation.

Video analysis

Five experts in the field of skiing biomechanics and sports medicine related to alpine skiing formed the analysis team. The analysis was organized into two stages. First, the analysts were asked to review the videos individually and complete one form for each injury case. The form included closed and open questions concerning (a) the skiing situation, (b) skier behavior, and (c) piste-related factors (Table 1). The relationship of injuries to falls/crashes was classified as follows: a skier sustaining an injury while still on his skis, albeit possibly out of balance and subsequently unable to recover, was said to have been injured while still skiing. Injuries were said to result from falling if they were caused by a crash, either from the initial impact or during subsequent sliding/tumbling. The analysts also reviewed the control runs carefully and completed one analysis form for each control to aid in their interpretation of the injury cases. This form was the same as for the injury cases, except for the questions concerning the contribution of injury. We did not conduct any training prior to the analysis; the experts were simply asked to analyse each case individually as many times as needed to form their own opinion before completing the forms. The analysts were provided with information registered through the FIS ISS for each case (sex, discipline, injured side and specific diagnosis). They were also provided with the time point where each of the cases and controls skied off course, as well as the assumed time of injury, determined by the first author (T. B.). If one of the analysts disagreed on the time of injury provided, the situation was reevaluated in stage 2 of the analysis. Stage 2 was a 2-day meeting where four of the five experts reviewed each case based on the forms completed by all analysts (one analyst was unable to attend). They were blinded to the opinion of the other analysts. Each video was evaluated as many times as needed to obtain agreement for all variables. If at least four of the five analysts had reached the same conclusion in their independent written analysis, a decision was said to have been reached. If three or fewer agreed in their independent written analysis, the variable was reported as “no agreement” unless all four analysts could agree on a decision in the meeting.

Statistical analysis

A chi-square test (95% CI, P < 0.05) was used to examine whether there was a difference between course sections regarding where the athletes skied off course/were injured. The course was divided into four course sections relative to the time spent until the incident occurred.

To determine in which course section the incident occurred, the time until the skier skied off course was expressed as the percentage of the winning time for the specific run (extracted from the result lists on the FIS website), as the absolute individual race time cannot be used because of differences between disciplines, race sites and genders.

Ethical approval

The study was reviewed by the Regional Committee for Medical Research Ethics, South-Eastern Norway Regional Health Authority, Norway (diary number 15355).

Results

Characteristics of the injury cases

Of all cases, 45 among males and 24 among females, there were 41 injuries to the lower extremities, 10 to the
upper extremities, 10 head injuries, and eight injuries to the back/thorax. Concerning injury severity, more than half of the injuries (n = 37) lead to absence from full participation in training and competition for more than 28 days. In the remaining cases, the reported absence was 8–28 days (n = 18), 4–7 days (n = 10), and 1–3 days (n = 3). In one case (head injury), data concerning time loss was missing. Most of the injuries occurred in the downhill discipline (n = 34), followed by giant slalom (n = 14), super-G (n = 12), and slalom (n = 9). Across the different alpine disciplines, there was a difference between course sections regarding where the cases (P = 0.001) and controls (P = 0.043) skied off course (Fig. 1). Almost half of the injuries (46%) occurred in the final section.

### Skiing situation and skier behavior

In most of the cases (n = 55), the skier was turning when the injury situation occurred, while 13 injuries occurred in relation to landing from a jump and one gliding after crossing the finish line. More than half of all injuries (59%) resulted from crashes, either from the initial impact (n = 20) or during subsequent tumbling/sliding (n = 21). In the remaining cases (n = 26), the injury occurred while the skier was still skiing; in five of these cases, the skier was able to recover without falling and in 21 cases, there was a subsequent fall. In two cases, the exact time of injury was not possible to judge, as the situation was not fully covered on the video. However, there were marked differences between knee injuries,
other lower extremity injuries and other injuries in the timing of injury related to falls (Fig. 2). In total, an unexpected bump on course was assumed to contribute to the injury in nine cases, either directly ($n = 2$) or indirectly ($n = 7$), influencing the skier’s balance and leading to fall.

Gate and safety net

In 45% of the injury cases ($n = 31$), there was inappropriate gate contact during the injury situation. Gate contact contributed to the injury in 21 cases (30%), either directly ($n = 8$), indirectly ($n = 12$) or both ($n = 1$). All impacts that contributed indirectly occurred prior to the injury; the skier skied inappropriately into/through the gate ($n = 5$) or hooked the gate with the inner ski ($n = 6$) or the arm ($n = 2$). One example is shown in Fig. 3. All impacts directly causing the injury occurred when the skier skied inappropriately into/through the gate ($n = 5$), hooked the gate with the inner ski ($n = 1$) or crashed into the gate after a previous fall ($n = 3$). Most of the gate-related injuries occurred in super-G ($n = 8$), followed by giant slalom ($n = 6$), downhill ($n = 5$), and slalom ($n = 2$). The gate released and/or broke in six cases, and the panel released in 12 of the 19 cases involving gate panels (in super-G, downhill, and giant slalom).

The skier was in contact with safety nets/material in 31 cases, contributing directly to the injury in six cases (9%). In these six situations, the skier, after falling, crashed into the net/material with the skis first ($n = 4$), or the skier skied directly into the net/material ($n = 2$). An example is shown in Fig. 4. In the remaining contact situations, the skier touched the net/material after sustaining an injury ($n = 21$), or the exact time of impact was out of sight in the camera view ($n = 4$). In total, the skier went under/over the safety net(s) and outside the piste in five cases. However, in all these cases, the assumed time of injury was prior to or at contact with the net.

Impacts to the head

The skier fell during the injury situation in 64 cases, and in 73% ($n = 45$) of these, the skier sustained one or several impacts to the head. The main impact was caused by contact with the snow surface ($n = 35$), safety net/material ($n = 9$), or a gate ($n = 1$). In two cases, the skier lost the helmet at the time of impact. Concussion was reported as the main diagnosis in 10 cases (see example in Fig. 5), and concussion was also reported in two other cases where the main injury (the most severe injury, based on the number of days of absence from training and competition reported) was to the lower extremities. All injuries leading to concussion ($n = 12$) occurred when the skier hit the head to snow surface, mainly in the speed disciplines ($n = 11$).

Injuries to the upper body

Injuries to the back/thorax ($n = 8$) were reported as rib ($n = 3$) and lower back contusions ($n = 3$), fractures to the lumbar spine ($n = 1$) and a lumbar muscle strain ($n = 1$). These injuries occurred in the speed disciplines, and the impact which contributed directly to the injury was caused by contact with the snow surface ($n = 5$) or safety net ($n = 2$) when falling (see example in Fig. 6). One injury situation was not fully covered on the video.

Injuries to the upper extremities ($n = 10$) were reported as ulna/radius fractures ($n = 3$), proximal humerus ($n = 1$), and metacarpal bones ($n = 2$). Other injuries to the upper extremities were ligament injury to the acromioclavicular joint ($n = 1$), shoulder dislocations ($n = 2$), and a shoulder muscle strain ($n = 1$). These injuries occurred both in the speed and technical disciplines.
and were a result of falling. In seven cases, the impact was with the snow surface (see example in Fig. 3), and in two cases, the skier fell and subsequently crashed into a gate. In the final case, the exact time of injury was not possible to judge from the video.

Injuries to the lower extremities

The knee injuries \( (n = 23) \) were mainly ACL \( (n = 16) \) or medial collateral ligament tears (MCL) \( (n = 5) \). The majority of these injuries occurred while the skier was still skiing \( (n = 19) \), before or without falling. In two of these cases, a bump on the course was assumed to contribute directly to the injury (see example in Fig. 7). In the remaining cases, the skier was out of balance unable to control the ski and stabilize the knee appropriately. In total, only three knee injuries occurred while falling, and these injuries were caused by contact with the snow surface \( (n = 1) \) or the safety net \( (n = 2) \). In the final case, the exact time of injury was not possible to judge from the video.

The other injuries to the lower extremities \( (n = 18) \) were reported as combined tibia/fibula fractures \( (n = 2) \), tibia fractures \( (n = 2) \), tibia contusion \( (n = 2) \), tibia bone bruise \( (n = 2) \), and talar bone bruise \( (n = 1) \). Of soft tissue injuries, there were thigh muscle strains \( (n = 2) \), calf muscle/tendon strains \( (n = 3) \), syndesmosis injuries \( (n = 3) \) and a lateral ankle sprain \( (n = 1) \). In seven cases, the skier was still skiing at the time of injury, and gate contact was assumed to contribute directly to the injury in five of these cases. The remaining injuries, which occurred while falling \( (n = 11) \), were caused by contact with the snow surface \( (n = 5) \), safety net \( (n = 2) \) (see example in Fig. 4), gate \( (n = 2) \), or a released ski \( (n = 1) \). The final case was not possible to judge from the video.

Discussion

We have described injury situations in professional ski racing based on systematic video analyses. The main findings were that most of the injuries to the head and
upper body resulted from crashes, while the majority of knee injuries occurred while still skiing. Gate contact contributed directly or indirectly to 30% of all injuries, while only 9% occurred at contact with safety nets/material. Almost half of the injuries (46%) occurred in the final section of the course.

Safety aspects

Perhaps the most notable finding of this study was that gate contact was involved in one-third of all injuries; the proportion was even higher (41%) if knee injuries were excluded. For a skier traveling at speeds of 60 to 80 km/h, which would be typical speeds in giant slalom and super-G, hitting a 300 g/m gate represents a substantial impact. Direct crashes/collisions into the gate were observed to cause nine injuries, e.g., tibia and fibula fracture, radius fracture, and contusion of the lower leg. Even more common were injuries indirectly caused by gate impacts, upsetting the skier’s balance and leading to a fall. Minimizing time loss when passing gates is obviously a key skill in the alpine disciplines and much effort has gone into gate design to minimize risk. Gates used in the WC must fulfill specific FIS requirements (FIS, 2011c, d, f). When athletes collide with the gates, the panel should release upwards from the poles, while the poles should not release or splinter. Gate specifications have been changed as recently as in 2008 and 2010 to increase safety (FIS, 2011c, e). Still, there may be a potential for further advances in pole construction and panel-release systems to reduce the impacts, which occur from an inappropriate gate contact. Reducing pole stiffness and minimizing the mass of the upright pole would reduce the impacts which occur when skiers hit the gate, and it seems reasonable to suggest that this would reduce injury risk.

Fig. 4. Injury situation leading to a fracture of the tibia and syndesmosis injury, right leg: (a; -2.76 s), the skier is out of balance entering a right hand turn. (b; -1.02 s), he falls to his right side and slides into the spill zone. (c; assumed time of injury), then he tumbles into the safety net with the skis first, causing the injury. (d; +2.74 s), the skier came to a full stop after contact with the safety net.
Different safety nets (A-nets, B-nets, triangular nets) and other safety measures (e.g., padding, slip sheets, air systems) are used extensively to protect the racers when accidents occur (FIS, 2011a, f). Spill zones (the area between the piste and the safety nets) are also cleared to allow skiers to slide unobstructed if they fall, and our analyses show that no injuries resulted from crashes with fixed objects or badly prepared spill zones. The purpose of the various safety devices is to absorb the kinetic energy of a falling skier, as well as to avoid them from crashing into danger areas (e.g., trees, pylons). Overall, our analyses showed that the safety measures that were in place were very efficient in the majority of cases. Although we observed that the skier had contact with safety nets/material in nearly half the cases, there were only six cases where the injury was judged to occur when the skier was stopped by the net/material. However, judging from the videos, the outcome could have been even worse had the skier not been stopped by the net. Nevertheless, it should be noted that we observed five cases where the skier tumbled over or under the net(s). In these cases, the injury had already occurred, but care should be taken to ensure that this cannot occur, as tragic outcomes could result if a skier were to go beyond the net to hit a stagnant object, e.g., a tree.

The injury risk was increased in the final section of the course, a finding supported by previous epidemiological studies, where approximately half of the injuries in ski racing were observed to occur during the final third of the course (Margreiter et al., 1976; Raas, 1982; Ekeland & Holm, 1985). Various explanations have been suggested; including a higher propensity for skier errors, through miscalculation, tiredness, and lack of concentration. When the skier is tired, the racing conditions and the aggessive equipment are even more challenging to

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Fig. 5. Injury situation leading to concussion: (a; −4.24 s), the skier hits some small bumps on the course, leading to an unbalanced position. (b; −2.82 s), an inappropriate gate contact with minor influence on the skier’s balance, leading to a left hand fall. (c; assumed time of injury), during tumbling backwards, the skier hits the head to the snow surface, contributing directly to the injury. (d; +4.40 s), he slides into the safety net after sustaining a concussion.
control. An obvious consequence of these observations is to ensure that skier fitness is adequate. It may also be worth discussing whether course setting should be less demanding in the final section, or if course length should be reduced to lessen injury risk. However, the injury distribution may differ between disciplines and it should be kept in mind that we were unable to provide separate analyses for each of the disciplines because of limited study power.

Fall injuries

We have recently published detailed results from video analyses of the mechanisms for knee injuries among WC skiers (Bere et al., 2011a, b), and it is therefore not surprising that most of the knee injuries observed occurred while the skier was still skiing. In contrast, we found that the vast majority of other injuries occurred while falling, and these injuries were caused by contact with the snow surface or objects on the course, such as safety nets/material, gates, or a released ski. Protecting a racer who is crashing, sliding or tumbling is therefore a priority. Today, racers are allowed to use protectors for all parts of the body. However, the protectors must be worn underneath the racing suit, except for forearm protection (used in super-G, giant slalom, and slalom) and shin protection (used in slalom; FIS, 2011b). In other high-velocity sports, such as motorcycling, an air bag system is integrated into the suit to reduce the risk of injury from high-energy impacts (Dainese, 2012). Similar systems are being tested for alpine ski racing, and our analyses suggest that these may have potential (FIS, 2012). Skin-tight racing suits are worn to reduce air resistance, and according to the FIS specifications of competition equipment, the material of the suit must be equally porous in all parts (FIS, 2011b). A material that causes more friction with the snow surface should reduce the amount of sliding when falling. However, we do not

Fig. 6. Injury situation leading to contusion of the posterior thoracic chest: (a; −1.80 s), the skier is out of balance at the jump take-off. (b; −1.30 s), bad take-off leads to an uncontrolled flight. (c; assumed time of injury), at landing, the skier hit the back to the snow surface, contributing directly to the injury. (d; +9.00 s), then he slides into the safety net after tumbling.
know whether more friction will also influence the amount of tumbling, and if injury risk would be reduced. A more cut-resistant material may also have the potential to protect the skiers from sharp ski edges, which was the cause of injury in one of the cases we analysed.

Our analyses showed that head impacts occurred in 45 cases, while a concussion or other traumatic brain injury was diagnosed and reported in only 12 of these. Underreporting of concussion is a well-known problem in sports (Benson et al., 2009). The diagnosis criteria for concussion have changed recently (McCrory et al., 2009); this could be one reason concussion may have been underreported in our study, as well. The use of a helmet is compulsory for all events, but current helmet standards for professional racers are similar to those for novice recreational skiers (McIntosh et al., 2011; FIS, 2011b). The majority of head injuries among WC athletes occur in the speed disciplines (Flørenes et al., 2009). Thus, it seems reasonable to develop a helmet standard specifically for ski racing, particular for the speed events (McIntosh et al., 2011).

Methodological considerations
Video analysis of real injury situations can provide a complete and accurate description of how injuries occur, but there are also some limitations. First, the interpretation of the videos may be affected by the video quality. We experienced in some cases that it was difficult to judge specific variables because of the camera position or camera view. Nevertheless, we feel confident that, in the majority of cases, the video quality was sufficient in order to describe the injury situation and various safety aspects we have addressed. Second, we cannot, in all cases, be sure of the exact time of injury. The experts were provided with the assumed time of injury for all cases, as determined by the first author (T. B.), who had substantial experience in video analysis of skiing injuries. However,
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the other analysts were encouraged to make their own decision and if one of them disagreed with the time point suggested, they were asked to report alternatives, which were then discussed in a plenary meeting. In eight cases, the assumed injury time point was revised. In some cases where the athletes crashed and subsequently tumbled, we cannot be sure of the exact time of injury. In these situations, we have used the first plausible incident/injury mechanism observed as the basis of our conclusion. In addition, the injury situation was not fully covered on the video in five cases; thus, the time of injury could not be determined and the mechanisms could not be assessed. Third, we had to exclude 25 cases from the video material, 22 among males and three among females, as we could not see any injury on the video. Of these, the reported injury was located to the knee (n = 10), lower back (n = 6), lower leg (n = 3), shoulder (n = 2), thumb (n = 2), head (n = 1), and chest (n = 1). Regarding the different alpine disciplines, they occurred in downhill (n = 10), slalom (n = 6), giant slalom (n = 5), and super-G (n = 4). However, with respect to the injury type, discipline, and sex, the injuries included reflect the injury pattern previously described in WC alpine skiing. Thus, we are comfortable that the injury situations included are representative for injuries among WC athletes.

**Perspective**

Our video analyses suggest that ski racer safety may improve by advances in equipment design. We found that the gates contributed to one-third of all injuries; improvement in pole and panel-release designs may therefore have a potential for reducing the impacts, which occur from an inappropriate gate contact. We also found that the majority of injuries to the head and upper body occurred while falling/crashing. To reduce the impacts to the body in these situations, advances in helmet standards, personal protective equipment, and racing suits should continue to be sought. In addition, as injury risk is highest in the final section of the course, it should be investigated to what extent athlete fatigue and/or course difficulties represent important contributors to injury.

**Key words:** Alpine ski racing, injuries, mechanisms, World Cup skier, video recordings.

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**Video analysis of injuries in World Cup alpine skiing**