Kinematics of Anterior Cruciate Ligament Ruptures in World Cup Alpine Skiing

2 Case Reports of the Slip-Catch Mechanism

Tone Bere,*† PT, MSc, Kam-Ming Mok,‡ MPhil, CSCS, Hideyuki Koga,†‡ MD, PhD, Tron Krosshaug,‡ PhD, Lars Nordsletten,§ MD, PhD, and and Roald Bahr,† MD, PhD

Investigation performed at the Oslo Sports Trauma Research Center, Department of Sports Medicine, Norwegian School of Sport Sciences, Oslo, Norway

Background: Based on visual video analyses of 20 injury situations, the main mechanism of anterior cruciate ligament (ACL) injury in World Cup alpine skiing, termed the “slip-catch” mechanism, was identified. This situation is characterized by a common pattern in which the inside edge of the outer ski catches the snow surface while turning, forcing the knee into valgus and tibial internal rotation. To describe the exact joint kinematics at the time of injury, a more sophisticated approach is needed.

Purpose: To describe the knee and hip kinematics in 2 slip-catch situations utilizing a model-based image-matching (MBIM) technique.

Study Design: Descriptive laboratory study.

Methods: Two typical slip-catch situations in World Cup alpine skiing reported through the International Ski Federation (FIS) Injury Surveillance System were captured on video with several camera views and high video quality. The injury situations were analyzed using the MBIM technique to produce continuous measurements of knee and hip joint kinematics.

Results: Within 60 milliseconds, the knee flexion angle increased rapidly from 26° to 63° in case 1 and from 39° to 69° in case 2. In the same period, we observed a rapid increase in internal rotation of the tibia with a peak of 12° and 9°, respectively. The knee valgus angle changed less markedly in both cases. We also observed a rapid increase of hip flexion as well as substantial hip internal rotation.

Conclusion: Knee compression and knee internal rotation and abduction torque are important components of the injury mechanism in a slip-catch situation.

Clinical Relevance: Prevention efforts should focus on avoiding a forceful tibial internal rotation in combination with knee valgus.

Keywords: knee injury; anterior cruciate ligament; professional alpine skiing; injury mechanism; injury biomechanics; video analysis

The American Journal of Sports Medicine, Vol. XX, No. X
DOI: 10.1177/0363546513479341
© 2013 The Author(s)
describe the kinematic characteristics of ACL injuries in sports more accurately. Using the MBIM technique, it is possible to produce continuous estimates of joint angles and positions and thereby estimate the time of injury by assessing abnormal joint configuration and sudden changes in joint angular motion.18

A detailed description of joint kinematics in injury situations is needed to improve our understanding of the injury mechanism.14 Continuous estimates of knee and hip joint angles, as well as a description of the time of injury, can give valuable information to develop targeted prevention measures to reduce the risk of ACL injuries. This information can be used in the development of sport-specific training methods, and in alpine skiing, it may be critical for assessing the potential for improvements in boot-binding systems. Thus, knowledge of the injury mechanisms in terms of the skiing situation, skier behavior, and joint kinematics that represent different domains can provide important clues to how injuries can be prevented.13 Kinematic data obtained from video recordings can also verify whether simulation studies (mathematical, cadaveric, or in vivo) actually correspond to what is seen in real injury situations.15

To describe the joint kinematics of ACL injuries in alpine skiing, utilizing the MBIM technique, at least 2 camera views in which the injured knee is shown clearly from different perspectives are needed for a good result.16 Unfortunately, injury video of this quality is rarely available. The objective of this study was to examine the detailed time course of knee and hip kinematics of 2 typical slip-catch situations in World Cup alpine skiing reported through the International Ski Federation (FIS) Injury Surveillance System.7,8

MATERIALS AND METHODS

Injury Case 1

One of the 10 slip-catch situations included in the previous visual video analyses2,3 was captured from 2 nearly perpendicular camera views, lending itself to this approach. A 29-year-old male alpine skier suffered an ACL tear of the right knee in a World Cup slalom race in Alta Badia, Italy, on December 17, 2007. Before the injury situation, the racer was late in line after a change of rhythm in the set course. He skied too directly into the entrance of a hairpin while leaning backward and tried to manage the next gate with an inner ski turn. The injury situation is described in Figure 1 (see also Video 1, previously published as a supplement to Bere et al2; available at http://ajsm.sagepub.com/content/39/7/1421/suppl/DC1). We obtained written informed consent from the athletes before the analyses as well as anthropometric data and measurements of the skis and boots.

Video Editing

Infront Sports & Media (Zug, Switzerland) provided video footage (analog BetaSP tape) of the first injury case. The analog file was digitized to a QuickTime (.mov) file (Episode Engine Admin v 5.0, Telestream Inc, Nevada City, California; Apple, Cupertino, California) with a DV25 PAL codec. Footage of the second case was obtained from Austrian Broadcasting Corporation (ORF, Wien, Austria) and received as a high-definition video file. For both cases, we deinterlaced 640 milliseconds of the video file to a tagged image file format (TIFF) using Adobe Premiere Pro (version 1.5, Adobe Systems Inc, San Jose, California) and Adobe Photoshop (version CS, Adobe Systems Inc) to increase the effective frame rate from 25 Hz to 50 Hz. In each case, manual synchronization between the different camera angles was performed using key events in each camera view (ie, ski’s contact with snow and skier’s contact with gate). The image sequences were then placed next to each other in a new video compilation and stored as an uncompressed audio video interleave (AVI) file using Adobe After Effects (version CS, Adobe Systems Inc). We utilized a skeleton computer model from Zygote Media Group Inc (Provo, Utah) for the skier matching process. This model consisted of 21 rigid segments as well as skis and poles. The model had 57 degrees of freedom and was hierarchically structured, using the pelvis as the parent segment. Pelvic motion was described by 3 rotational and 3 translational degrees of freedom, and the motion of the remaining segments was then described with 3 rotational degrees of freedom relative to their parent, for example, the shank relative to the thigh.
The dimensions of the skeleton model were based on direct anthropometric measurements of the injured skier. The skis were assumed to be rigidly connected to the feet. Tibial rotation was matched using the orientation of the ski boot as guidance, and the rotation was fully assigned to the knee, as the ski boot was assumed to prevent ankle rotation. In addition, the skin-tight racing suit had reference points that were used to assess the body configuration, such as thigh and shank rotation.

RESULTS

Injury Case 1

We analyzed 640 milliseconds of the injury situation, and the outer ski was airborne until 420 milliseconds into this video sequence. At that moment, the skier regained snow contact with the outer ski, which drifted away from the body’s center of mass. In the index frame, the outer ski catches the inside edge abruptly. (D) At +140 milliseconds, the skier falls backward to her left.
abruptly and simultaneously with the rapid increase in knee flexion, while the hip internal rotation stayed nearly constant at approximately 35°.

**Injury Case 2**

We observed that when the outer ski drifted away from the body’s center of mass in a right-hand turn, the valgus angle of the left knee increased suddenly from 0° to 12° within 60 milliseconds (Figure 4C). During the next 120 milliseconds, the valgus angle stayed almost constant, while the outer ski was still drifting on the snow surface, trying to regain grip. Then, when the inside edge of the ski suddenly caught into the snow (Figure 4D), we observed that the knee flexion angle increased rapidly from 39° to 69° within 60 milliseconds. We also observed a rapid increase of tibial internal rotation with a peak of 9° in the same period. The knee valgus angle decreased slightly from a peak of 14°, observed...
120 milliseconds before the peak tibial internal rotation. Similar to case 1, we also observed that the hip flexion angle increased abruptly and simultaneously with the rapid increase in knee flexion, while hip internal rotation did not change substantially. In case 2, the hip was internally rotated at approximately 65°.

**DISCUSSION**

We observed sudden changes in knee and hip joint angles, in both cases, when the inside edge of the outer ski caught the snow surface. Within 60 milliseconds, the knee flexion angle increased from 26° to 63° in case 1 and from 39° to 69° in case 2. In the same period, we observed a rapid increase in tibial internal rotation with a peak of 12° and 9°, respectively. The knee valgus angle changed more gradually in both cases. We also observed a rapid increase of hip flexion and substantial hip internal rotation.

**Slip-Catch Kinematics**

The leg was abruptly and forcefully compressed from a relatively straight position in both cases. This motion pattern indicates that there is likely a high compression force of the knee joint involved. Previous studies support that a combination of knee joint compression, tibial internal rotation, and knee valgus is an important component of the ACL injury mechanism in team sports such as handball, basketball, and football.\[12,13,21,23,24,26\] A proposed hypothesis is that noncontact ACL injuries seem to occur approximately 40 milliseconds after initial contact and that knee abduction loading and lateral compression generate tibial internal rotation and anterior tibial translation due to the joint surface geometry and possibly quadriceps drawer, resulting in an ACL tear.\[13\] Interestingly, the motion pattern observed in the current study closely resembles the motion pattern observed for noncontact ACL injuries. However, there are forces and moments involved in alpine skiing that make a slip-catch situation different from a noncontact ACL injury situation.

In a slip-catch situation, we have observed that the skier is out of balance backward/inward.\[2\] This will generate an internal tibial torque by 2 mechanisms. First, a carving ski will rotate inward because of the ski’s self-steering effect.\[20\] In a balanced position, the skier will be able to follow the path of the ski by using appropriate technical approaches,\[20,29\] but when the skier is out of balance, he or she may be unable to adjust to the rotary motion. Thus, the self-steering effect of the ski can generate an internal tibial torque by forcing the ski to carve inward (Figure 5). Second, when a lateral load is applied behind the projection of the tibial axis, the ski will act as a lever to internally rotate the tibia relative to the femur.\[30\] A more backward lean will give a longer moment arm to the tibial axis and thus a larger internal rotation torque (Figure 6A). Although it is difficult to reliably measure small internal rotations of the knee using the MBIM method, the large hip internal rotation combined with pressure on the medial side of the rear ski makes this scenario very likely.

In addition, it has been reported that edging a carving ski while turning is associated with knee valgus angles up to 12°.\[4,10,33\] An increased knee valgus angle will likely also contribute to an increased abduction torque (Figure 6B). Catching an inside edge, while being out of balance backward/inward, may therefore represent a serious hazard to the ACL.\[2,18,30\]

It has been suggested that in a backward-bending posture while skiing, boot-induced anterior drawer\[6\] can also strain the ACL.\[14\] In addition, it has been proposed that a quadriceps contraction may cause tibial anterior drawer when the skier tries to recover from an unbalanced position backward on slightly flexed knees.\[9,22\] Because of clothing and limited picture resolution, we were not able to evaluate whether tibial anterior drawer was present in these slip-catch situations. However, based on the sudden changes in joint angles observed with the MBIM technique, we suggest that the ACL injury was caused by simultaneous knee compression and knee internal rotation and abduction torque. It therefore seems likely that the
ACL ruptured shortly after the onset of large changes in knee flexion.

Methodological Considerations

This study has shown that we can use the MBIM technique to provide continuous measurements of knee and hip kinematics during 2 slip-catch situations representative of a series of similar injuries from World Cup alpine skiing. It is difficult to determine the accuracy of the current matching process, but the nearly perpendicular camera views and the high video quality made it possible to achieve a good match between the skier and the skeleton model for the video images in all frames. Even though this technique is subjective and dependent on the operator’s ability to perform the model matching consistently, the method is likely to be far more accurate than visual video analysis. An advantage of analyzing a skiing injury with this method is that tibial rotation relative to the femur can likely be matched more accurately than for team sports injuries based on the orientation of the skin and boot. The tibial rotation was fully assigned to the knee, as the stiff and tight ski boot was assumed to prevent ankle rotation. This assumption has not been validated but is supported by previous studies. We also used reference points on the skin-tight racing suit to determine rotation of the thigh and shank. Similar to traditional 3-dimensional motion analysis with skin markers, there are mainly 2 sources of error that may affect hip rotation, knee rotation, and valgus angle when utilizing the MBIM technique: (1) movement of the reference points on the racing suit relative to the underlying soft issue, and (2) movement of the soft tissue relative to the underlying bone. Because of the material specifications of the racing suit, we expect minimal movement of the suit relative to the skin, but it is difficult to predict how the soft tissue moves with respect to the underlying bone. It has been recognized that soft tissue artifact is the most significant source of error in human movement analyses. Thus, we should keep in mind that the estimated kinematics will not be a true representation of the skeletal motion, even though the matching process is performed optimally. Three experts gave their opinion on the matching results, and the matching process was then adjusted iteratively until a consensus was reached. We performed sensitivity analyses of the matching process in which the femur was axially rotated inward and outward to ensure that we presented the best possible estimates of knee and hip joint angles. It would have been preferable to have more cases, but video of sufficient quality for this advanced analysis is rare: of all the ACL injury videos we collected from 6 World Cup seasons (2006-2012), only these 2 cases were suitable.

CONCLUSION

We were able to assess sudden changes of knee and hip angles for 2 slip-catch situations representative of a series of similar injuries from World Cup alpine skiing by using the MBIM technique. This study supports previous visual video analyses, suggesting that knee compression and knee internal rotation and abduction torque are important components of the injury mechanism in a slip-catch situation.

More than half of the ACL injuries in World Cup alpine skiing occur in a slip-catch situation, and to reduce the risk of these injuries, it is important to avoid a situation in which the knee is rapidly forced into internal rotation and valgus while slightly flexed. Even though a relatively precise time sequence of knee and hip angles was obtained for 2 representative slip-catch situations, we need to analyze several cases, utilizing the MBIM technique, to evaluate whether these estimates are general trends and to quantitatively describe the joint kinematics of the slip-catch mechanism.

ACKNOWLEDGMENT

The authors thank the International Ski Federation staff and officials for all practical support in collecting the injury data, as well as the athletes, coaches, and medical staff involved. They also thank Anna Banach and Infront Sports & Media, and Stefan Proglhof and Austrian Broadcasting Corporation (ORF), for help with video capture and editing.

REFERENCES