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Mechanisms of injuries in World Cup alpine skiing

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Table of contents

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List of papers

This dissertation is based on the following original research papers, which are referred to in the text by their Roman numerals:

I. Bere T, Flørenes TW, Krosshaug T, Haugen P, Svandal I, Nordsletten L, Bahr R. A systematic video analysis of 69 injury cases in World Cup alpine skiing. Scand J Med Sci Sports 2013: [Epub ahead of print] Jan 10, doi:10.1111/sms.12038.

II. Bere T, Flørenes TW, Krosshaug T, Nordsletten L, Bahr R. Events leading to anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases. Br J Sports Med 2011: 45: 1294-1302.

III. Bere T, Flørenes TW, Krosshaug T, Koga H, Nordsletten L, Irving C, Muller E, Reid RC, Senner V, Bahr R. Mechanisms of Anterior Cruciate Ligament Injury in World Cup Alpine Skiing: A Systematic Video Analysis of 20 Cases. Am J Sports Med 2011: 39:1421-1429.

IV. Bere T, Mok KM, Koga H, Krosshaug T, Nordsletten L, Bahr R. Kinematics of Anterior Cruciate Ligament Ruptures in World Cup Alpine Skiing: Two Case Reports of the Slip-Catch Mechanism. Am J Sports Med, submitted.

Abbreviations

ACL	Anterior Cruciate Ligament
BIAD	Boot-Induced Anterior Drawer
EMG	Electromyography
FIS	International Ski Federation
FIS ISS	FIS Injury Surveillance System
MBIM	Model-Based Image-Matching
MCL	Medical Collateral Ligament
MRI	Magnetic Resonance Imaging
OSTRC	Oslo Sports Trauma Research Center
WC	World Cup
WSC	World Ski Championship

Summary

Introduction

The International Ski Federation (FIS) Injury Surveillance System (ISS) has reported that during the five-month winter season, one in every three World Cup (WC) alpine skiers sustains an injury. Similar to recreational skiers, the most common problem in ski racers is knee injuries, and the most frequent specific diagnosis is a complete rupture of the anterior cruciate ligament (ACL). Our knowledge of injury mechanisms in alpine skiing is limited, particularly among competitive skiers. Video of real injury situations contain important information of what took place when the injury occurred. This information, in turn, can form the basis for injury prevention strategies. The main aim of this thesis was therefore to describe the mechanisms of injuries in WC alpine skiing, based on systematic analysis of video recordings.

Methods

Injuries reported through the FIS ISS for three consecutive WC seasons (2006-09) were obtained on video. In total, 69 time-loss injuries from WC competitions were included for the analysis. Five experts analyzed all the injury cases to evaluate characteristics of the skiing situation, skier behavior, as well as piste-related factors (Paper I). Further, the ACL injuries (n=20) were analyzed in more detail. Ten WC coaches performed visual analysis of each injury 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 & course setting, 5) visibility, snow & piste conditions and 6) any other factors (Paper II). In addition, seven international experts in the field of skiing biomechanics and sports medicine related to alpine skiing performed visual analysis of each ACL injury case to describe the inciting event in detail i.e. the skiing situation, skier behaviour and biomechanical characteristics at the time of injury (Paper III). Two ACL injury situations were analyzed using a more advanced method, the model-based image-matching (MBIM) technique, to produce continuous estimates of knee and hip angles at the time of injury (Paper IV).

Results

Of all the 69 injury cases, the skier was most frequently turning (n=55) or landing from a jump (n=13) when the injury situation occurred, and almost half of the injuries (46%) occurred in the final fourth of the course (Paper I). Gate contact contributed to 30% of the injuries, either

directly or indirectly, while 9% occurred at contact with safety nets/material. Most of the injuries to the head and upper body (96%) resulted from crashes, while the majority of knee injuries (83%) occurred while still skiing. Skier technique, skier strategy and specific race conditions were assumed to be the main contributors to the ACL injury situations. Skier errors, mainly technical mistakes and inappropriate tactical choices, were the dominant factors (Paper II). Three main categories of ACL injury mechanisms were identified, which we termed the Slip-Catch (n=10), Landing Back-Weighted (n=4) and the Dynamic Snowplow (n=3) (Paper III). The Slip-Catch mechanism was characterized by a common pattern where the skier lost pressure on the outer ski while turning, 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 MBIM analyses revealed that the knee flexion angle increased rapidly by more than 30° within 60 ms in both cases (Paper IV). In the same period, we observed a rapid increase in tibia internal rotation with a peak of approximately 10°, while the knee valgus angle increased more gradually. Based on the visual analyses, internal rotation of the tibia and knee valgus were also observed for the Dynamic Snowplow mechanism, while the Landing Back-Weighted mechanism was characterized by a common pattern where the skier was out of balance backwards in-flight after a jump and landed on the ski tails with nearly extended knees (Paper III). The suggested loading mechanism in this situation was a combination of tibiofemoral compression and an anterior tibial translation.

Perspectives

Based on the current studies, which are the first to describe the mechanisms of injuries in WC alpine skiing, we suggest that safety for the skier may improve by advances in equipment design. Improvement in pole and panel-release designs may have a potential for reducing the impacts which occur from an inappropriate gate contact. To reduce the impacts to the body while falling/crashing, advances in helmet standards, personal protective equipment and racing suits should continue to be sought. The ACL injury situations, which occur mainly while skiing, before or without falling, develop rapidly due to high skiing speeds. Although there is probably no single solution which will prevent ACL injuries from occurring, risk may be reduced from a combination of measures which can reduce the energy involved in a potential injury situation and give the skier more time to react and adjust. Factors which need to be considered should include the equipment (the ski-plate-binding-boot system), snow conditions (icy and aggressive snow), course setting and speed, and athlete preparation and conditioning. Whether a training program 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 recognize the risk situations and, if possible, avoid these altogether or respond by 'bailing out' in time.

Introduction

Alpine skiing

Background

Skiing is a major winter sport in many countries, and the total number of skiers worldwide is estimated to be approximately 200 million (Hunter, 1999). Alpine skiing is the most popular activity on the slopes, followed by snowboarding and telemark skiing (Ekeland & Rødven, 2006; Sulheim et al., 2011). The skiing population represents a broad spectrum of the public, varying in all age groups and skill levels. Skiing is enjoyed by beginners and recreational skiers as well as professional ski racers.

In the 1990s, alpine skiing experienced a remarkable boom worldwide after the introduction of carving skis. A review from 2005 reported that more than 80% of all skiers use carving skis, and traditional skis can hardly be found in the market or in ski rental shops (Horterer, 2005). Carving skis are shorter, more flexible and have an increased sidecut (lower ski radius) compared to traditional skis. In addition, a binding plate is mounted between the ski and the binding, whereby the standing height of the skier is increased 1-2 cm. This makes it possible to increase the ski edge angle while turning. A review of biomechanical research in alpine skiing, reported that the more waisted and more flexible skis, together with a greater on-edge angle, make it possible to carve turns with much smaller turning radius (Muller & Schwameder, 2003). It is expected that turns with carving skis require better sagittal balance and an improved edge steering ability to remain centrally positioned over the ski, compared to turns with traditional skis.

The International Ski Federation (FIS) is committed to promote and develop the different disciplines of skiing and snowboarding, both as recreational activities and competitive sports. The federation was founded in 1924 during the first Olympic Winter Games in Chamonix (France) (International Ski Federation, 2012c). In the beginning, FIS consisted of 14 member nations, while today it has expanded into more than 110 national ski associations. Alpine skiing became a part of the Olympic disciplines in 1936 (International Ski Federation, 2012d), and today more than 50% of all FIS competitors are alpine skiers. As many as 15,972 alpine competitors were registered from 81 nations in 2011.

World Cup alpine skiing

The FIS World Cup (WC) is the highest competitive level in alpine skiing, with the exception of the World Ski Championship (WSC) and Olympic Winter Games. Participation in the FIS WC is determined on the national quota of the skier‘s national team and the skier‘s FIS points (International Ski Federation, 2011f). The FIS points are given based on the skier's racing results, which is determined by the racing time measured to .01 seconds (International Ski Federation, 2011f). To achieve a good racing time/skier performance, the skier trajectory and speed are crucial (Federolf, 2012). However, the skier's ability to turn where intended and control the speed is expected to be dependent on several external and internal factors, as alpine skiing is a typical outdoor sport where the athlete has to ski challenging courses and are required to manoeuver through gates in different snow and weather conditions.

Competitive alpine skiing mainly consists of five different events/disciplines for females and males; slalom, giant slalom, super-G, downhill and a combined event. The slalom discipline is characterized by the shortest course and the quickest turns. In the WC, the course has a vertical drop of 180-220 m for males and 140-220 m for females (International Ski Federation, 2011f). A slalom course involves technical difficulties and is set with different combinations of gates. Giant slalom is a similar version to the slalom, but with fewer, wider and smoother turns and a higher vertical drop. The distance between the nearest poles of two successive gates should not be less than 10 m (International Ski Federation, 2011f). Slalom and giant slalom are called the "technical" disciplines, because of the technical difficulties throughout the courses (Neumayr et al., 2003). In both these events, each skier makes two runs down two different courses on the same slope, and only the first 30 skiers from the first run are qualified for the second run. Both runs take place on the same day, usually with the first run held in the morning and the second run in the afternoon. The fastest total time (both runs included) determines the winner.

Super-G stands for super giant slalom and combines the precise turns of giant slalom with more high speed turns, jumps and gliding phases. The course is longer than a giant slalom course and the vertical drop is higher. The distance between two gates is 15-25 m (International Ski Federation, 2011f). Downhill is characterized by the longest course, the highest speed and the highest vertical drop of the alpine disciplines. The vertical drop in the WC are 800-1100 m for males and 450-800 m for females (International Ski Federation, 2011f). The course includes challenging turns, jumps and gliding phases, and the skiers are required to participate in at least one timed official training, normally organized two or three days before the race. Because of the high speed (80-120 km/t at the WC level), super-G and downhill are called the "speed" disciplines (Neumayr et al., 2003). In these events, each skier makes only one single run down the course in each race, and the fastest time determines the winner.

The combined event represents the final result calculated by adding race times of single events or runs (International Ski Federation, 2011f). In WC, the combined event is a so-called super-combined event, which consists of one run in downhill (or super-G) and a single run in slalom, usually held on the same day at the same venue. The combined events are contested independently of the regular discipline events.

With respect to the different alpine disciplines; slalom, giant slalom, super-G and downhill, the skiers may be separated into "specialists" (competing in either technical or speed disciplines) and "all-rounders" (competing in both technical and speed disciplines) (Neumayr et al., 2003).

Due to safety and functional reasons, gates used in the WC must fulfill specific requirements determined by the FIS, based on lab-tests with standardized methods (International Ski Federation, 2011c; International Ski Federation, 2011d). A gate usually consists of an inside turning pole and an outside pole (in the slalom discipline), or an inside gate and an outside gate, consisting of two poles and a panel between (in giant slalom, super-G and downhill) (International Ski Federation, 2011f) (Figure 1). The specific requirements are set, such that the poles and panels should work as intended during normal gate contact, and as far as possible, avoid that the skier get injured by them during inappropriate gate contact. According to the FIS specifications (International Ski Federation, 2011c), the turning pole (inside gate) must have a bending device at the level of the snow surface, and the mass of the upright pole should not exceed 300 g/m. In addition, the material must be made of a non-splintering material (plastic, plasticized bamboo, etc.). The poles should project about 1.8 m out of the snow, and they should have a diameter between 29-32 mm and a wall thickness of minimum 2.0 mm. The panel, which is fastened between two poles and has a size of approximately 0.75 x 0.50 m, should release along the poles upwards when the athletes collide with the gate (International Ski Federation, 2011d).

Figure 1. Different type of gates used in the WC. To the left: An inside slalom turning pole with a bending device at the level of the snow surface (photo by Robin Smith). To the right: An inside giant slalom gate, consisting two poles with bending devices and a panel in between (photo by Agence Zoom). Permission to reproduce these images has been granted by Robin B. Smith and Riikka Rakic, 2012.

In all alpine disciplines, the athlete has to adapt speed and trajectory to his technical skills and his individual self-responsible judgement. However, for safety reason, a combination of different security nets and cushioning material is used to protect the racers from accidental situations (International Ski Federation, 2011a; International Ski Federation, 2011f) (Figure 2). A-nets (high safety nets) are used around steep difficult turns, in the landing area after jumps, and in compressions with small fall zones. B-nets (safety fences) are used where there is a potential large crash area, usually set in three rows covering a distance of 6-10 m. Triangular nets and cushioning material should be used as additional material to protect immobile objects on the slope (trees, lift supports, rocks, etc.), while an air system (paddoc) is used for the finish area. In addition, slip sheets (which are produced in different tensile strengths and are cut resistant) covering the other materials, if needed.

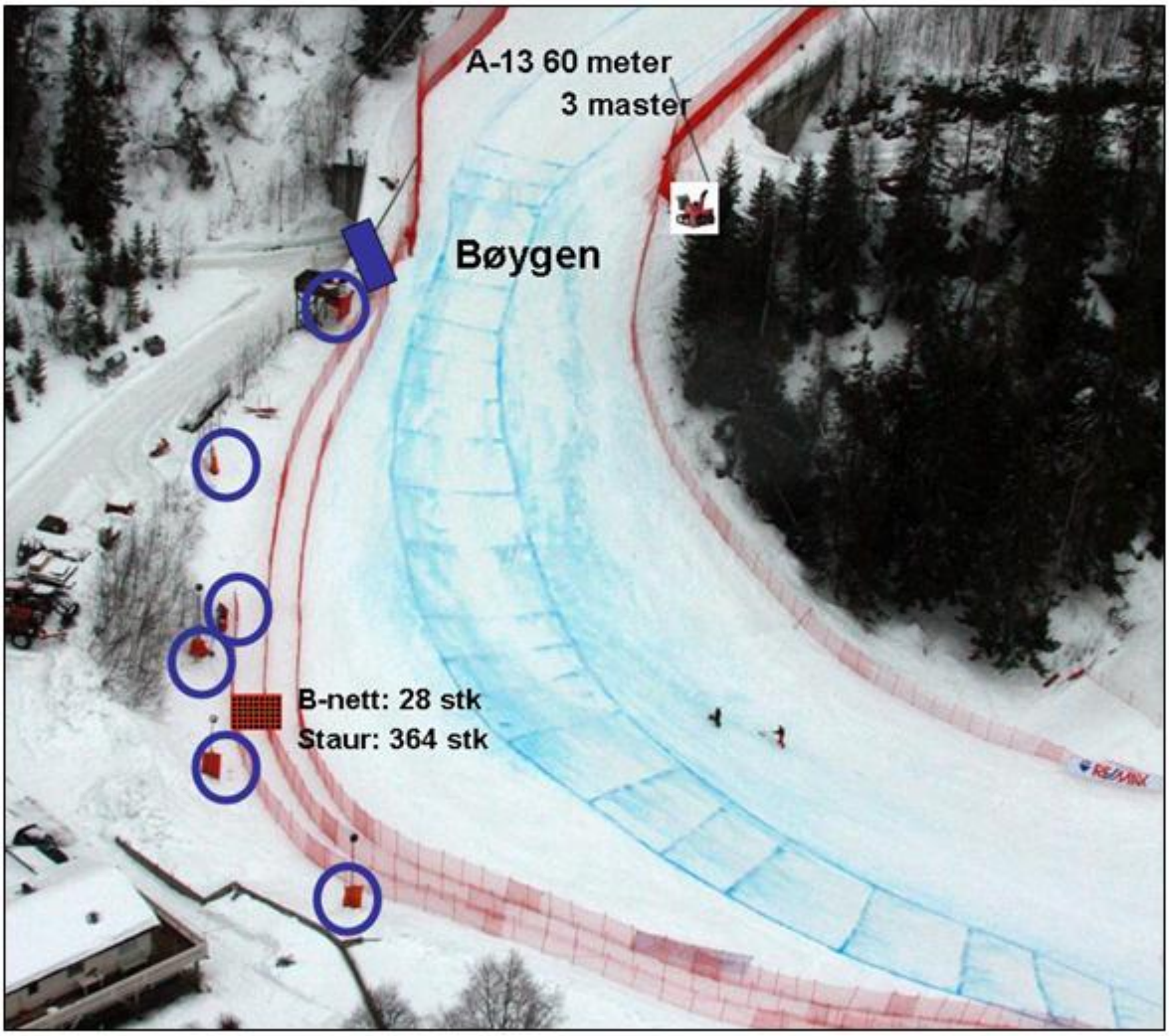

Figure 2. Safety material used for the WC downhill in Kvitfjell, Norway, 2009. Down to the left; B-net (set in three rows) and cushioning material (in blue circles). Up to the right; A-net with slip sheets. The photo is taken from the handbook for on-course staff at Kvitfjell, 2009. Permission to reproduce has been granted by Svein Mundal, 2012.

Skier equipment

High performance in alpine skiing requires equipment which is individually fine-tuned for competition conditions (Tesch, 1995; Neumayr et al., 2003; Reid, 2010). Competition equipment includes all items of equipment used by the skiers, including clothing and implements that serve a technical function. However, specific rules for equipment are determined by the FIS to make the sport safe and fair (International Ski Federation, 2011b).

Alpine skis used by competitive skiers are made of various material specially adapted to the racing conditions. The ski's geometrical (length, width and shape) and physical (flexural and torsional stiffness) properties play an important role in determining the skis' deformation while turning and their "performance" on the snow (Reid, 2010; LeMaster, 2010). The width of a carving ski changes continually along its length giving a smooth, curved edge profile referred to as the ski's sidecut (LeMaster, 2010). Three widths are of particular importance in studying how the ski will perform on the snow; the maximum width at the shovel, the minimum width at the waist and the maximum width at the tail. The sidecut radius refers to the radius of a circle that intersects the side of the ski at the shovel, waist and tail points while the ski is laying flat on a planar surface (LeMaster, 2010) (Figure 3). Thus, the sidecut radius does not correspond to an actual turning radius, as it does not consider how the ski will deform when edged and loaded. The ski's length, width and radius must conform to clear rules set by the FIS. These specific requirements vary between the different alpine disciplines and for females versus males (International Ski Federation, 2012a).

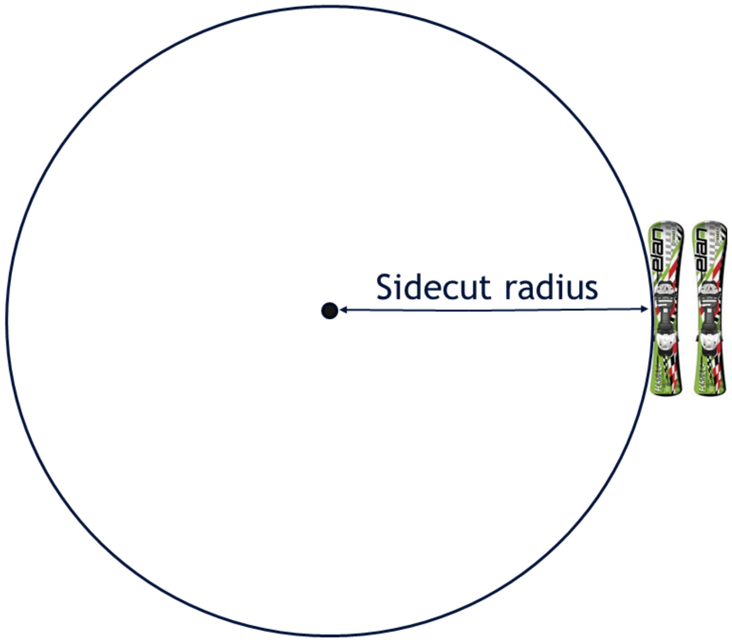

Figure 3. The sidecut radius of a carving ski.

When a carving ski is edged and loaded on the snow surface, it can make it turn as it moves forward with only minimal input from the skier, due to the ski's geometrical and physical properties. In other words, the ski turns itself. This behaviour characteristic of the skis has been referred to as the ski's "self-steering effect" (LeMaster, 2010). However, the skier can regulate his/her trajectory and speed by controlling the skis position, thus turning should be seen as an interaction between the ski, snow and the skier (Reid, 2010).

When describing the ski's motion along the snow surface, two processes are generally recognized, namely, carving and skidding (LeMaster, 2010). During carving, the ski shovel digs into the snow surface creating a groove in which the rest of the ski follows. A point along the ski's edge that is carving is said to follow in the track cut by proceeding ski segments with minimal or no lateral displacement. In contrast, a ski that is sliding sideways across the snow surface as is moves forward is said to be skidding. A point on the ski's edge that is skidding does not follow in the path of preceding points but rather shears through new snow as it moves across the snow surface. Carving and skidding can occur at the same time along different segments of a ski's length. Thus, a complete carving turn or a complete skidding turn probably never occurs in practice (Reid, 2010).

Bindings are the link to attach the boots to the skis, and safety bindings should release when the torsion or impact is high enough. Modern "multi-release" bindings release in respond to several forces; (1) a lateral motion of the toe, (2) a forward lean at the heel, (3) a backward lean (upward release at the toe) and some bindings may also release in response to (4) lateral motion of the heel (Koehle et al., 2002). Correct adjustment and maintenance of the bindings are important for the binding release function. Mounting of anti-vibration plates between the bindings and boots is permitted, but the maximum height (distance between the bottom of the running surface of the ski and the floor of the ski boot sole) is regulated at 50 mm (International Ski Federation, 2011b). The robust ski boots enclose the foot firmly, while at the same time allowing the movement necessary for skiing techniques. The ankle should have the room it needs to move, but at the same time allowing the transfer of every steering movement to the ski. A raise of the boot sole is permitted to increase the standing height of the skier, but the maximum height is regulated to 43 mm for WC skiers (International Ski Federation, 2011b).

The use of a helmet is compulsory for all events. Only helmets whose shell and padding cover the head and ears are permitted, however soft ear protection is allowed for slalom events. All helmets must show a smooth top surface for safety reason (International Ski Federation, 2011b). The helmets shall be CE marked and conform to international standards, such as the EN (European Standard) 1077, the ASTM (American Society for Testing and Materials) F2040 or the SNELL S98/RS 98 (McIntosh et al., 2011; International Ski Federation, 2011b). The current helmet standards for professional racers are similar to novice recreational skiers. However, for alpine speed events (downhill and super-G), the helmets must fulfill an additional requirement; the maximum deceleration according to the norm EN 1077 Class A, must not exceed 230 g in a 1.5 m drop test against a flat anvil (normal standard is 250 g). The helmet must bear a specific marking ("DH/SG") applied by the manufacturer to conform that such requirement is fulfilled.

Skin-tight racing suits are worn to reduce air resistance. Competition suits and any clothing worn beneath, such as underwear, must have a minimum air permeability of 30 litres per m^2/s under 10 mm of water pressure (International Ski Federation, 2011b). The suits must be equally porous in all parts, both from the outside in and from the inside out. The racers are allowed to use additional personal protectors for all parts of the body, such as to the shoulder/scapular region, back/chest, arms and legs. However, the protectors must be worn underneath the plumbed racing suit, except of forearm protection (used in super-G, giant slalom and slalom) and shin protection (used in slalom). A back protector, which is intended to protect the skier's back against external forces, is recommended and must be worn under the racing suit. The back protector has to adapt to the anatomical bend of the skier's spine and lay flat against the body. The top edge of the back protector has to be situated in the area of the thoracal column and may not reach above the 7th cervical vertebrae. The maximum thickness has to be in the middle part and may not exceed 45 mm. Back protectors designed to improve aerodynamic properties are forbidden (International Ski Federation, 2011b).

Skiing biomechanics

As skiing should be seen as an interaction between the skier, skis and the snow, there are mainly three external forces acting on the skier, which influence the skiing mechanics. These forces are the gravitational force, the snow reaction force and the air drag force (LeMaster, 2010) (Figure 4).

The gravitational force works at the skier's center of gravity toward the center of earth. The skier's gravitational force can be divided into two force components. One component acts parallel to the slope and causes the acceleration of the skier, which is the primary force acting to increase the skier's speed. The second component works perpendicular to the slope, which accelerates the skier towards the snow and influences the ski-snow interaction. The size of each of these components depends on the angle of the slope (Reid, 2010). The snow reaction force works opposite to the gravitational force. One component of the snow reaction force is the snow friction force, which acts along the contact area between the ski and snow. This force is directed opposite to the skier's velocity and decelerates the skier. However, due to low friction between the ski and snow, the snow reaction force acts approximately perpendicular to the ski's longitudinal axis (LeMaster, 2010). When turning, this reaction force can be divided into two forces; one working vertically against the gravitational force and the other working towards the center of rotation, the centrifugal force. This force will push the skier to the outside of the turn, and the size of this force depends on the turning radius and skiing speed. A smaller turning radius and a higher velocity cause higher centrifugal forces (LeMaster, 2010). The final external force acting on the skier is the air drag force or air friction force. This force is directed opposite to the skier's velocity and decelerates the skier. The magnitude and orientation of the air drag force is determined by e.g. the air density, the athlete's position and the frontal area that is exposed to the wind (Reid, 2010).

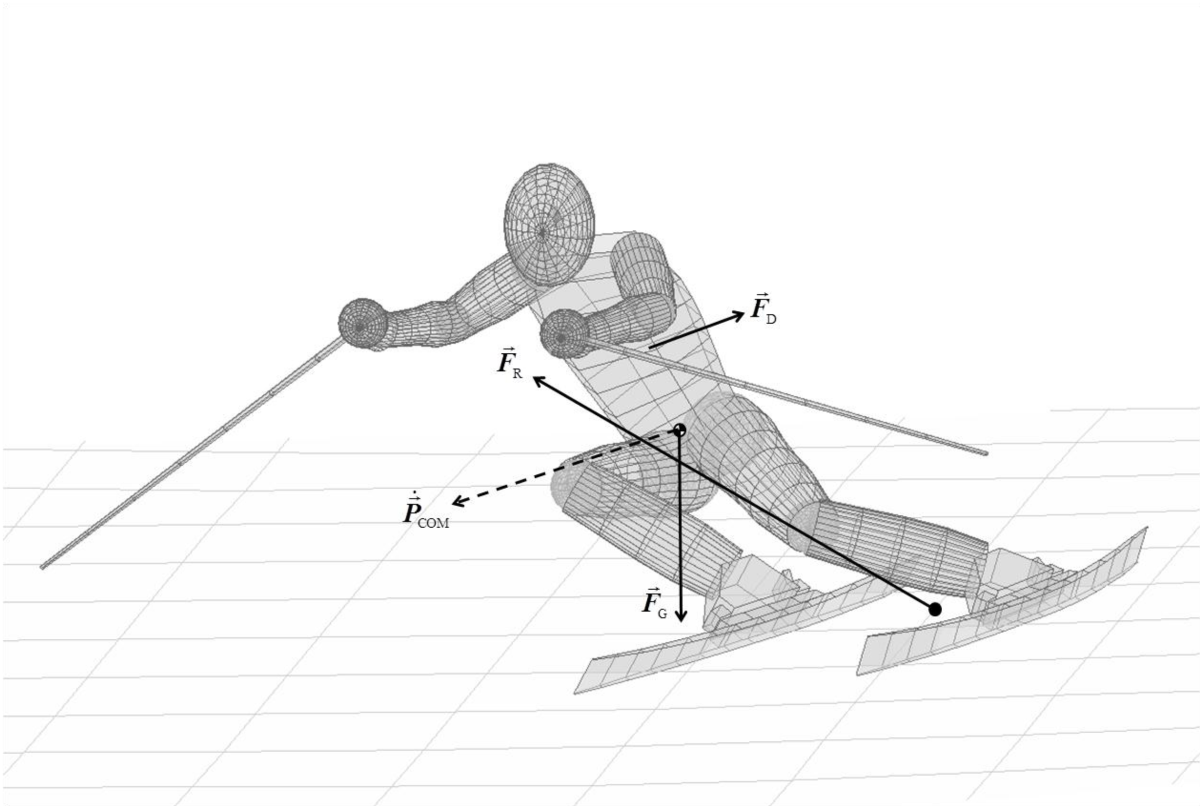

Figure 4. The external forces acting on a skier during turning; the gravitational force (F_G), snow reaction force (F_R) and air drag force (F_D). In addition, the figure shows the center of mass velocity vector ($\dot{P}_{COM}$). The figure is taken from Reid, 2010. Permission to reproduce has been granted by Robert Reid, 2012.

To adjust the external forces and control the self-steering effect of the ski as efficiently and safely as possible, the skiers use different technical and tactical approaches (Reid, 2010; LeMaster, 2010). For example, the skier can control his trajectory and speed by regulating the ski edge angle (lateral action in the frontal plane) and the distribution of pressure along the ski-snow interface (forward/backward action in the sagittal plane). In addition, proper alignment of the body segments is essential to stay in balance. Thus, high performance in ski racing requires a high level of technical and tactical skills, which are dependent on several physiological and psychological variables, such as aerobic and anaerobic power, muscle strength, coordination, flexibility, motivation, concentration and the ability to sustain stress (Tesch, 1995; Neumayr et al., 2003).

Epidemiology

Skiing has been called “the fastest non-motorized sport on Earth” and “the riskiest sport undertaken by adults on a routine basis” (Boutin & Fritz, 2005). Unfortunately, the fun of skiing is combined with a risk of injury. Two top level skiers from the Canadian alpine ski team described their experiences on being injured as follows (Bianco et al., 1999):

> “I knew immediately what I had done. You just know, you feel it, the dreaded pop when you‘re tearing a ligament. I knew it would be a year before I would be back at any type of competitive level.”

> “There was pain because I had surgery, pain because I knew my career was over. It was probably the moment that I suffered the most in my life, mentally and physically. There was pain all over.”

The long-term goal of epidemiological research on sport injuries is to prevent injuries. The injury prevention research process has been described by van Mechelen et al. (1992) (Figure 5). The first step is to identify the magnitude of the injury problem through injury surveillance. Main questions of interest are: What is the injury incidence? What is the most frequent injury type and location of injury? And what is the severity of injury? In the second step, the risk factors and injury mechanisms that play a part in the occurrence of injuries must be identified. What are the causes for injury? And why and how do injuries occur? The third step is to introduce measures that are likely to reduce the future risk and/or severity of injuries through interventions. And finally, the effect of the measures must be evaluated by repeating the first step. In addition, a 6-stage model has been presented which incorporates the implementation of effective prevention strategies into real life (Finch, 2006). However, it is important that the prevention process is based on reliable and valid data collected in the first and second step to introduce effective prevention strategies.

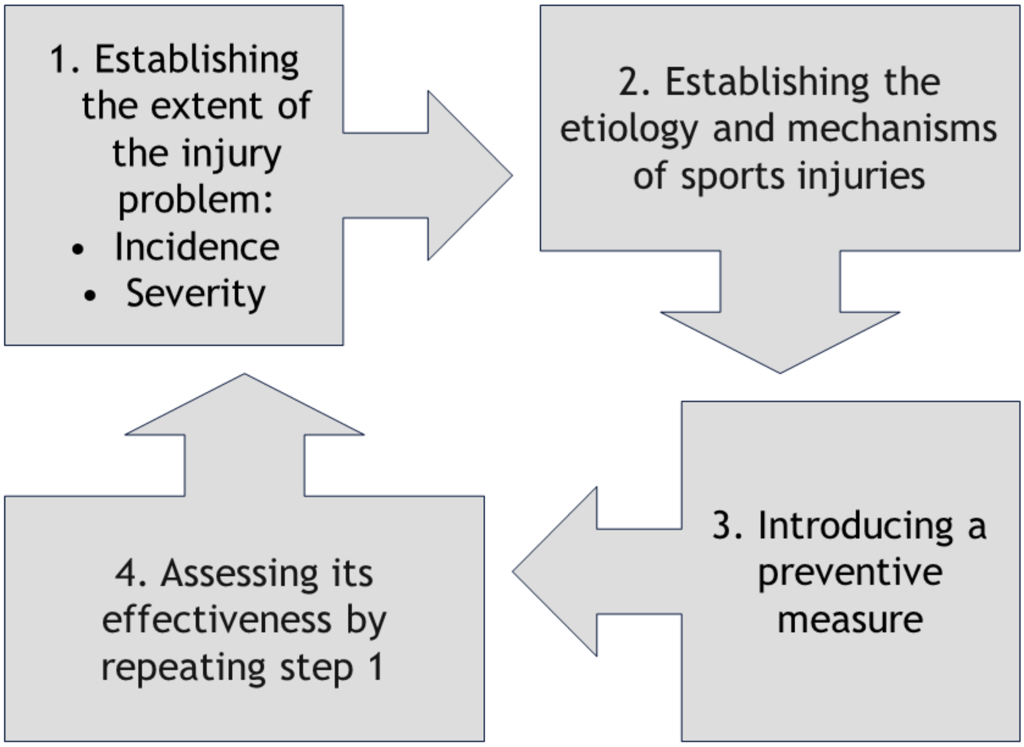

Figure 5. The 4-step sequence of injury prevention research (retrieved and reproduced from van Mechelen et al. 1992).

A complete understanding of injury causation requires knowledge about the complex interaction between internal (individual-related) and external (environmental-related) risk factors (Meeuwisse et al., 2007). Internal risk factors include e.g. age, gender, technical and tactical skills, previous injuries and risk taking behaviour, while external risk factors include e.g. snow and weather conditions, safety measures on the slope and equipment used by the skier (type of ski, binding, boots, etc.). The sum of these risk factors and the interaction between them make the athlete susceptible for injury, but an inciting event is necessary to cause an injury. The inciting event is usually called the "injury mechanism" in epidemiological studies of sport injuries, but the term is often widely used and not well defined. Bahr & Krosshaug (2005) outlined several components of the injury mechanism, which could be of interest to understand and prevent injury. These include the specific sport situation, the specific athlete‘s behaviour and movement, as well as detailed biomechanical characteristics of anatomical structures (Figure 6). A precise description of the injury mechanism is essential to understand the multi-factorial cause of injury. To understand which component of the apparent mechanisms that is actually responsible for an injury, Meeuwisse (2009) emphasized the need to identify mechanisms of no injury situations, as well.

To distinguish between the mechanisms of injury and the mechanisms of no injury, the critical component of the inciting event that ultimately causes an injury may be uncovered.

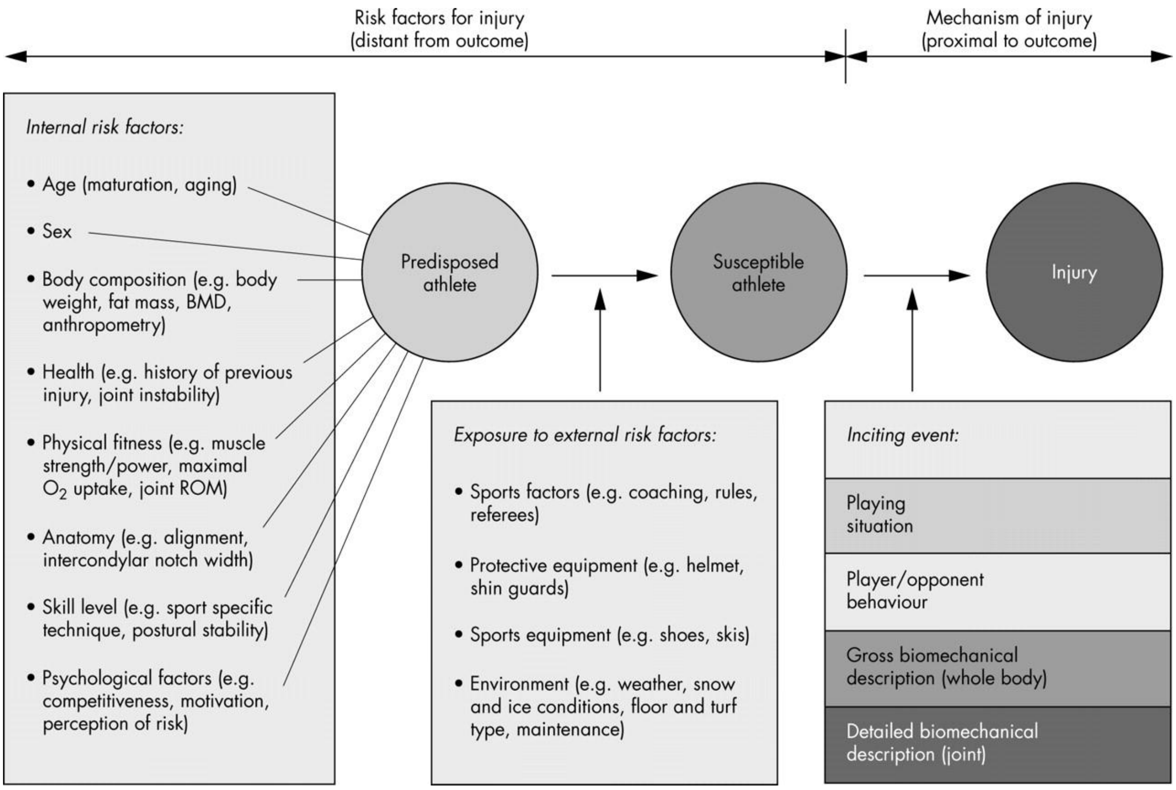

Figure 6. A comprehensive model of injury causation. BMD, Body mass density; ROM, range of motion. The figure is retrieved from Bahr & Krosshaug, 2005; based and developed on the epidemiological model of Meeuwisse, 1994. Permission to reproduce has been granted by Roald Bahr, 2012.

Injury definition

In epidemiological research on sport injures, it is well known that variations in injury definitions and injury collection procedures may lead to significant differences in results and conclusions (van Mechelen et al., 1992; Junge & Dvorak, 2000). A consensus statement concerning injury definitions and collection procedures was therefore established in football (soccer) (Fuller et al., 2006). However, the aim of the statement was to provide the basis for a common injury definition and injury collection procedures for other sports, as well. The consensus group defined an injury as "any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities". An injury that results in a player receiving medical attention is referred to as a "medical attention" injury, and an injury that results in a player being unable to take a full part in future football training or match play is referred to as a "time-loss" injury (Fuller et al., 2006).

In studies among recreational skiers in ski resorts, an injury is usually defined a "medical attention" injury, i.e. an injury sustained by a skier who is treated by or consulted with the ski patrol or base-lodge clinic/first aid room staff after a skiing accident (Ekeland & Rødven, 2009; Sulheim et al., 2011; Kim et al., 2012). In competitive skiing, different injury definitions have been used. Based on the consensus document on injury surveillance in football, Flørenes et al. (2009) reported "all injuries that occurred during training and competition and required attention by medical personnel", while Westin et al. (2012) reported injuries that "occurred during training and competition, which made it impossible for the skier to participate fully in skiing or physical training not on snow for at least one training session or competition". In a previous study, serious injuries among WC skiers were defined as "impairment to health and working ability for a period of more than 20 days as a result of the accident" (Raas, 1982), while in the Junior WSC of 1995, an injury was defined as "one that required the skier to be transported or treated by the medical team, with an Injury Severity Score from 1 to 75" (Bergstrom et al., 2001). The Injury Severity Score is described later in this thesis.

Injury incidence

Most studies concerning injuries in alpine skiing describe injuries among recreational skiers, and injuries are mainly reported by ski patrols and medical staff at ski resorts in Europe, Australia and the US. The majority of the studies present a total injury incidence for all kinds of skiing activities on the slopes, and the injury incidence is usually expressed as the number of injuries per 1,000 skier-days (skier-visits). As early as in the 1950s, injuries were reported from Sun Valley in the US. Earle, Moritz & Saviers (1962) reported an injury incidence of 7.4 injuries per 1,000 skier-days between 1952 and 1961. Since that time, the injury incidence has decreased considerably. A long-term study from Vermont (USA) shows that the injury incidence declined by 44% from 1972 to 1994, indicating an incidence of 2.5 injuries per 1,000 skier-days in 1994 (Johnson et al., 1997). The most recent data from the Vermont study, reported an injury incidence of 1.9 injuries per 1,000 skier-days in 2006 (Johnson et al., 2009). This data corresponds very well with recent data from ski resorts in Norway and Austria, reporting an injury incidence (injuries/1,000 skier days) of 1.4 (Ekeland & Rødven, 2009) and 1.3 (Burtscher et al., 2008), respectively.

The injury incidence among competitive alpine skiers has been expressed as (1) number of injuries per 100 or 1,000 athletes per season, (2) number of injured skiers per 1,000 athletes per season, (4) number of injuries per 1,000 runs, (5) number of injuries per 1,000 ski hours and (6) number of injuries per 100 months (Table 1). Data from the FIS Injury Surveillance System (ISS) have reported that during the five-month WC season, one in every three skiers sustains a time-loss injury, and in competition the incidence was 9.8 injuries per 1,000 runs (Flørenes et al., 2009). The high injury rate among elite skiers is supported by a five-year cohort study among alpine skiers at Ski High schools in Sweden (Westin et al., 2012). They found that 71% of the skiers reported a previous injury at the time they entered the study, and 50% of the skiers sustained at least one injury during their study period at the schools. The incidence was reported as 1.7 injuries per 1,000 ski hours and 3.1 injuries per 100 months. In addition, previous studies have reported that 70-80% of the world‘s best skiers suffer at least one serious injury during their careers (Margreiter et al., 1976; Raas, 1982; Ekeland et al., 1997). The high rate of severe injuries is emphasized by a study from the elite French national teams, reporting an anterior cruciate ligament (ACL) injury incidence of 8.5 per 100 skier-seasons (Pujol et al., 2007). In contrast, some small studies reported a low total injury incidence during the 1994 Olympic Winter Games (Ekeland et al., 1996a), the Junior WSC of 1995 (Bergstrom et al., 2001) and among Norwegian alpine ski racers during the 1981/1982 winter season (Ekeland & Holm, 1985). However, these results should be interpreted with caution, due to low power study.

It is difficult to make a direct comparison between epidemiological studies in alpine skiing, because of different injury definitions and injury registration methods used in the literature. However, it is well documented that the injury rate among recreational skiers has decreased considerably the last 20-30 years, while the injury rate in competitive alpine skiing is still high.

Table 1. Epidemiological studies on injury rate in competitive alpine skiing

Reference (publ. year)	Study design	Population	Injury definition	Injury recording	Exposure	Outcome (injury rate)
Margreiter et al. (1976)	Retrospective survey	World class ski racers; 40 females and 74 males	Previous injuries that affect the general health > 20 days	Athlete interview/questionnaire, 1972-1974	Not appropriate	82% reported at least one previous injury
Raas (1982)	Retrospective survey	World class ski racers; 72 females and 78 males	Previous injuries that affect health/working ability > 20 days	Athlete interview/questionnaire, 1978-1981	Not appropriate	83% reported at least one previous injury
Ekeland & Holm (1985)	Prospective survey	Racers (n=25,445) in 251 races, 1981-1982	Injuries occurring in Norwegian ski competitions	Injury reports completed by a referee from the NSF	Number of racers during the season	1.6 injuries or 1.4 injured skiers per 1,000 racers
Ekeland et al. (1997)	Retrospective survey	Alpine racers competing in the 1994 Olympics (n=256)	Previous injuries leading to absence from skiing > 20 days	Athlete questionnaire completed during the Olympics	Not appropriate	72% of the 54 respondents (only 30%) reported > one injury
Ekeland et al. (1996a)	Prospective survey	Alpine racers competing in the 1994 Olympics (n=555)	Injuries occurring during the events (incl. off. training)	Questionnaire/medical reports	Number of started runs	1.9 injuries per 1,000 runs
Stevenson et al. (1998)	Retrospective survey	1010 competitive skiers in the US	Previous knee injuries	Athlete questionnaire (sent out directly) during the 1995 summer season	Not appropriate	27% reported previous injury. Female-male ratio of ACL injury 3.1
Bergstrøm et al. (2001)	Prospective survey	Alpine racers in the 1995 JWSC; 452 female and 546 males	Injuries treated by medical team with ISS from 1 to 75 (incl. off. training)	Questionnaire/medical reports	Number of started runs	4.0 injuries per 1,000 runs
Pujol et al. (2007)	Retrospective survey	French competitive skiers (n=379), 1980-2005	ACL ruptures	Review of the national database and corresponding medical reports	Number of skier-seasons	8.5 ACL ruptures per 100 skier-seasons
Flørenes et al. (2009)	Prospective cohort study	521 WC alpine skiers	Injuries with medical attention during training and competitions	Athlete interviews at the end of the seasons 2006/07 and 2007/08	Number of athletes and runs per season	36.7 injuries per 100 athletes per season and 9.8 injuries per 1,000 runs
Westin et al. (2012)	Prospective cohort study	431 skiers at Swedish Ski High schools, 2006-11	Injuries with absence from ≥ one training or competition	Monthly report from each athlete by e-mail	Number of ski hours and ski months	1.7 per 1,000 ski hours and 3.1 per 100 months

Injury pattern

Since the 1980s, injury location, expressed as the body part injured, has changed in recreational skiing (Johnson, 1995; Hunter, 1999; Koehle et al., 2002; Johnson et al., 2003). This is probably related to the improvement in ski equipment like higher and stiffer plastic boots, more modern ski bindings and the introduction of carving skis (Johnson, 1995; Natri et al., 1999; Horterer, 2005; Burtscher et al., 2008). Lower leg fractures have become less common, while injuries to the knee and upper extremities have become more common (Warme et al., 1995; Ueland & Kopjar, 1998; Johnson et al., 2009). The most remarkable transition reported is from the Vermont study (Johnson et al., 2009). They found that serious knee ligament injuries, usually involving the ACL, increased by 268% between 1972 and 1992, and then declined by 37% between 1992 and 2006.

However, injuries to the lower extremities still account for up to 50% of all injuries in alpine skiing (Ekeland & Rødven, 2009; Johnson et al., 2009). A rupture of the ACL and the medial collateral ligament (MCL) are the most frequent injuries, and it is suggested that beginners suffer more combined knee ligament injuries, while an isolated ACL injury is more common among experienced skiers (Greenwald & Toelcke, 1997; Langran & Selvaraj, 2004). An ACL injury is also often seen in combination with meniscus injuries (Duncan et al., 1995) and bone bruises (Speer et al., 1995).

Almost 19% of all injuries are upper extremity injuries, and the most frequent injury sites are the thumb and the shoulder (Davidson & Laliotis, 1996; Kocher & Feagin, 1996; Kim et al., 2012). "Skier's Thumb" accounts for one-third of all injuries to the upper extremities. This injury is a rupture of the ulnar collateral ligament in the first metacarpophalangeal joint. However, a disruption of tendons, such as the extensor pollicis longus and adductor pollicis, as well as intra-articular fractures may also occur (Browne et al., 1976). The most common injuries of the shoulder are rotator cuff strains and anterior glenohumeral dislocations and subluxations. Other frequent injuries located to the shoulder are acromioclavicular separations and clavicle fractures (Kocher et al., 1998).

Spinal injuries seem to account for approximately 7% of all injuries in recreational skiing (Johnson et al., 1997; Ekeland & Rødven, 2006), and only 9% of these require surgery for neurological deficit or instability (Tarazi et al., 1999; Floyd, 2001). Head injuries account for 17-19% (Furrer et al., 1995; Ekeland & Rødven, 2006; Sulheim et al., 2006; McIntosh et al., 2011), and Sulheim et al. (2006) reported that almost 25% of all head injuries were referred to a physician or hospital by the ski patrol for further assessment or treatment (potentially severe injuries). It seems like head injury is the most frequent reason for hospital admission among recreational skiers (Furrer et al., 1995; Ackery et al., 2007; Ruedl et al., 2011a).

In competitive skiing, two cohort studies have described the injury pattern among WC athletes (Flørenes et al., 2009) and skiers at Swedish Ski High schools (Westin et al., 2012). In addition, a few studies, mainly from the 1980s and 1990s, have reported injuries among athletes during single events or from single national ski associations (Margreiter et al., 1976; Raas, 1982; Ekeland & Holm, 1985; Ekeland et al., 1996a; Ekeland et al., 1997; Stevenson et al., 1998; Bergstrom et al., 2001; Pujol et al., 2007). Both Flørenes et al. (2011) and Westin et al. (2012) found that 58% of all injuries reported among the athletes were located to the lower extremities. Similar to recreational skiing, the distribution of injuries to the lower leg and ankle seem to have decreased since the 1980s, while knee injuries have become more common (Margreiter et al., 1976; Raas, 1982; Ekeland & Holm, 1985; Westin et al., 2012). Flørenes et al reported that the most commonly injured body part among WC athletes was the knee (36%), followed by lower leg (12%), lower back/pelvis/sacrum (12%), hand/finger (9%), head/face (8%) and shoulder/clavicle (7%). Across the different body parts, the most common injury type was joint and ligament injuries (44%), followed by fracture and bone stresses (19%). An ACL injury (14%) was the most frequent specific diagnosis, which is supported by previous studies (Stevenson et al., 1998; Viola et al., 1999; Pujol et al., 2007).

Injury severity

In the consensus statement of football injuries, injury severity is defined as "the number of days that have elapsed from the date of injury to the date of the player‘s return to full participation on team training and availability for match selection" (Fuller et al., 2006). The severity classification of time-loss injuries, based on time of absence from training and/or matches, is described as slight injuries (0 days), minimal (1-3 days), mild (4-7 days), moderate (8-28 days), severe (> 28 days) and career ending. In addition to the duration of time loss, other injury outcome measures may also be used to describe the severity of injures in different sports, e.g. descriptions of individual or team performance, type of treatment, costs associated with rehabilitation, working time lost, permanent damage, duration of the injury and quality of life (van Mechelen, 1997; Fuller et al., 2006), but these have not been used in alpine ski injury research.

In alpine skiing, studies have first of all used the Injury Severity Score to describe the severity of injury (Bergstrøm et al., 1993; Furrer et al., 1995; Ekeland et al., 1996b; Bergstrom et al., 1999; Bergstrom et al., 2001; Bergstrom & Ekeland, 2004). This score is a tool to assess an overall injury severity for patients with multiple injuries. The score is derived and calculated from the

Anatomical Injury Score (Baker et al., 1974). This score classifies individual injuries by seven body regions on a six-point ordinal severity scale ranging from one (minor) to six (lethal) (Greenspan et al., 1985). The Injury Severity Score is the sum of the squares of the highest Anatomical Injury Score code in each of the three most severely injured body regions (Baker et al., 1974). In the Junior WSC, the total Injury Severity Score was 17 and the mean Injury Severity Score was 4.25 per injury (Bergstrom et al., 2001). The respective values for the Olympic Winter Games were 17 and 5.5 (Ekeland et al., 1996a).

Other previous studies have used absence from training and competition for more than 20 days as their definition of a severe injury (Raas, 1982; Ekeland et al., 1997). However, return to full participation in training and competition, or participation with individual adjustment, should be described to make the definition clear. Flørenes et al. (2009) and Westin et al. (2012) graded the severity of injury according to the duration of time loss defined by Fuller et al. (2006). Among WC athletes, 81% of all injuries were time-loss injuries and, of these, 38% were severe (time loss > 28 days), 33% moderate (time loss 8-28 days), 19% mild (4-7 days) and 10% minimal (1-3 days) (Flørenes et al., 2009).

Injury risk factors

A number of factors are thought to be associated with the risk of injury in alpine skiing. Epidemiological studies have related the risk of injury to specific characteristics of the skier, the skier equipment and/or environmental factors. Associations have been examined in case-control and cohort studies, and several risk factors have been identified among recreational skiers. However, some studies have examined risk factors for skiing and snowboarding together. In addition, not all studies have used multivariate logistics regression analyses to consider potential confounding factors. In competitive alpine skiing, only three cohort studies are available concerning injury risk factors among the athletes (Flørenes et al., 2009; Raschner et al., 2012; Westin et al., 2012). In addition, a qualitative study has reported on a range of potential risk factors in WC alpine skiing based on interviews with expert stakeholders within FIS (Spörri et al., 2012). Available studies on risk factors in alpine skiing are shown in Table 2.

Internal risk factors

Age

Reviews have reported that in recreational skiing, skiers younger than 16 years are assumed to have the highest risk of injury (Koehle et al., 2002; Hagel, 2005). Of these, the age group 13-16 years is commonly at higher risk than the youngest age group (under 10 years old). However, there is evidence that the relationship between age and injury risk changes depending on injury type and location of injury. For example, case-control studies have reported that the youngest age group (under 13 years old) is at highest risk for lower leg fracture (Ekeland et al., 1993; Ekeland et al., 2005; Sulheim et al., 2011).

In contrast to recreational skiing, a prospective survey among Norwegian competitive alpine skiers reported that the injury incidence in national racers was higher among athletes over 16 years than athletes under 16 years (Ekeland & Holm, 1985). This is supported by Raschner et al (2012), who reported that the ACL injury rate among young racers (14-19 years) was highest for females at 19 years and males at 17 years. The age-related risk of injury in competitive skiing is, however, not fully understood. In addition, it is not clear whether age differences in injury risk are related to skiing ability and skier equipment.

Gender

Several studies have suggested that female skiers have twice the occurrence of serious knee injuries compared to males (Davidson & Laliotis, 1996; Greenwald & Toelcke, 1997; Ekeland et al., 2005; Ekeland & Rødven, 2006; Ruedl et al., 2011c), while males have a significantly higher occurrence of shoulder injuries, spinal injuries and head injuries than females (Greenwald et al., 1996; Tarazi et al., 1999; Floyd, 2001; Levy et al., 2002; Ekeland & Rødven, 2006; Ackery et al., 2007). A case-control study reported that when skill level was considered, there was still a highly significant difference in injury pattern between genders, but the total injury incidence was the same (Shealy & Ettlinger, 1996).

It is unknown whether the gender-related risks of injury are caused by anatomical and physiological differences between females and males, or different skiing pattern and skiing behaviour. Regarding the ACL injury risk, it is suggested that environmental factors, such as cold temperature and snowfall (Ruedl et al., 2012a), as well as personal factors, e.g. leg dominance (Ruedl et al., 2012b) may potentially have a higher impact on injury risk among females than males. In addition, two case-control studies have identified the preovulatory phase of the menstrual cycle as a risk factor for ACL injury (Beynnon et al., 2006; Ruedl et al., 2009b). On the other hand, it is also suggested that male recreational skiers are more prone to risk-taking behaviour on the slopes compared to females (Ruedl et al., 2010).

A recent meta-analysis concerning ACL injury in ball/team sports, reported a female-male ratio of 4.5 in handball, 3.5 in basketball and 2.7 in football (Prodromos et al., 2007). The reason for the gender difference in ACL injury risk in these “pivoting” sports is unknown, but hypotheses have been suggested such as differences in lower extremity alignment, notch dimension, ligament size, level of skill, muscle strength and coordination. It has also been suggested that there may be gender differences in ligament laxity, possibly related to cyclic hormonal effect (Arendt & Dick, 1995; Hewett, 2000; Biedert & Bachmann, 2005; Hewett et al., 2007).

In competitive alpine skiing, Flørenes et al. (2009) reported an overall higher injury incidence in males compared to females, expressed as number of injuries per 100 athletes per season (RR 1.42), as well as number of injuries per 1,000 runs (RR 2.05). However, there were no significant gender differences when looking into subgroups, such as time-loss injuries, knee injuries and ACL injuries, in particular. Gender-related differences were neither reported among skiers at High Ski schools in Sweden during five seasons (Westin et al., 2012), nor in elite French national skiers sustaining ACL injuries from 1980 to 2005 (Pujol et al., 2007). In addition, a retrospective cohort study among expert skiers (ski patrols and ski instructors) in the US, reported no gender difference in risk of ACL injury during a period of six years (Viola et al., 1999). A possible explanation could be that the energy involved in an injury situation among competitive skiers is so high that anatomical and physiological differences between females and males do not matter.

On the other hand, a retrospective cohort study among ski racers at a Skigymnasium in Austria, reported that the ACL injury rate (exposure data missing) was higher in females than males (RR 2.3) (Raschner et al., 2012). This is supported by a few and small surveys among professional alpine skiers (Bergstrom et al., 2001; Ekeland et al., 1997; Ekeland et al., 1996a; Stevenson et al., 1998). However, these studies should be interpreted with caution, due to low study power.

Skiing ability, experience and performance

Skiing ability has been shown to be a frequent and perhaps the most important internal risk factor for injury among recreational skiers, particularly among children (Langran & Selvaraj, 2004; Hagel, 2005; Ekeland et al., 2005; Sulheim et al., 2011). However, it is unsure whether the high injury risk among low skilled skiers and beginners may also be related to improper adjustment and tuning of the equipment.

In contrast to recreational skiing, surveys among competitive skiers have suggested that skiers at the highest competitive level are most prone to injury (Margreiter et al., 1976; Raas, 1982; Baer, 1982; Ekeland et al., 1997; Pujol et al., 2007). A direct comparison of injury risk between WC athletes (Flørenes et al., 2009) and younger ski racers (Westin et al., 2012; Raschner et al., 2012) is unfortunately not possible from the three cohort studies available, because of methodological differences, such as the injury definition and the registration of injury and exposure. Among skiers at the same competitive level, Bergstrøm et al. (2001) found no relation between injury risk and performance/FIS points. However, Spörri et al. (2012) reported that younger WC athletes, in particular women, may not always be sufficiently prepared to enter the WC, and may therefore be at higher risk of injury, due to lack of fitness and early fatigue. This is supported by Raschner et al (2012), who suggested that core strength is a critical factor for ACL injuries in young ski racers.

External risk factors

Equipment

It is clear that the modern "multi-release" binding and the modern ski boots have dramatically reduced the risk of lower leg fractures, but they have not protected the knee from serious ligament injuries (Natri et al., 1999; Koehle et al., 2002). A number of studies have reported an association between knee injury and the failure of the bindings to release. In a retrospective survey of ACL injured recreational skiers in Japan (1995-1997), Urabe et al. (2002) reported that 77 of the 80 respondents lost their balance and fell, subsequently spraining the knee, before the binding released.

Goulet et al. (1999) performed a case-control study to investigate to which extent improper adjustment of the bindings is an injury risk factor among recreational skiers. They found a two-fold greater overall risk of injury in children under 13 years when the adjusted binding deviated more than 20% from recommended values according to international standards. In addition, Ekeland et al. (1993) found in a case-control study that no-self testing of the bindings was identified as a risk factor for injuries to the lower extremities. Therefore, it is recommended that the bindings should be correctly adjusted by professionals at least once a year (Burtscher et al., 2008) and controlled by self-release tests every day before skiing (Ekeland & Nordsletten, 1994). The adjustment of bindings has shown to be highly inadequate among alpine skiers, both in recreational and competitive skiing (Ekeland & Lund, 1985; Ekeland et al., 1993; Nordsletten et al., 1996; Goulet et al., 1999; Urabe et al., 2002).

It is also reported that the entire ski-binding-plate-boot system is thought to be a key risk factor for injury according to a group of expert stakeholders within FIS (Spörri et al., 2012). They suggested that the system is too direct in force transmission and too aggressive in the ski-snow interaction. They also reported that it is too difficult to get off the edge once the ski is carving. As a result, it is hard to control the equipment if the athlete loses his/her balance.

Characteristics of the slope, course and discipline

Of injuries occurring on groomed slopes, a case-control study among recreational skiers suggested that skiing in a snow park (with spectacular elements) increases the risk of severe injuries compared with skiing on other slopes (Goulet et al., 2007). A review examined the worldwide epidemiology of traumatic brain and spinal injuries in snowboarding and alpine skiing (Ackery et al., 2007), indicated that the incidence of these injuries is increasing, and the increase coincides with the development and acceptance of acrobatic and high-speed activities on the slope.

Among competitive skiers, Flørenes et al. (2009) reported that the highest incidence (injury per 1,000 runs) was found in the downhill discipline (17.2), followed by super-G (11.0), giant slalom (9.2) and slalom (7.4). There was a significant difference between slalom compared to downhill (RR 3.48) and super-G (RR 2.23), as well as for giant slalom compared to downhill (RR 1.87). These findings are supported by previous surveys reporting a higher number of injuries in downhill than the other disciplines (Raas, 1982; Ekeland & Holm, 1985; Ekeland et al., 1997). Across all disciplines, studies have reported that almost half of the number of injuries occurs during the last third of the course (Margreiter et al., 1976; Raas, 1982; Ekeland & Holm, 1985; Ekeland et al., 1997). It is unknown whether the risk of injury is directly related to specific characteristics of the different disciplines, and whether injuries in the final section of the course are related to skier errors, such as miscalculation and fatigue, versus environmental factors e.g. poor visibility and challenging race course conditions. Thus, one aim of this thesis was to describe the injury situations in terms of the skier behaviour and piste-related factors.

Table 2. Epidemiological studies examining risk factors in alpine skiing.

Reference (publ. year)	Study design	Population	Study period	Injury definition	Potential risk factors	Statistical method	Outcome (risk factor identified)
Beynnon et al. (2006)	Case-control	Recreational; 46 injured skiers, 45 uninjured controls	2000-2004	ACL injuries in females	Phases of the menstrual cycle	T-test, Chi-square test Logistic regression	Prevulatory vs. postovulatory phase (OR 3.22)
Ekeland et al. (1993)	Case-control	Recreational; 132 injured skiers, 316 uninjured controls	1985-1986	Injuries treated by the medical center at four Norwegian ski resorts	Personal- and equipment related factors for LEER injury (n=140)	Fisher-Irwin or KologorovSmirnov test	Children < 10 years, beginner, low experience, no skiing instruction, no self-testing of the bindings
Ekeland et al. (1996b)	Case-control	Recreational; 328 injured skiers, 316 uninjured controls	1985-1986	Injuries treated by the medical center at four ski resorts	Ungroomed slope (powder skiing)	Fisher-Irwin or KologorovSmirnov test	Groomed slopes vs. powder skiing (OR 1.20)
Ekeland et al. (2005)	Case-control	Recreational; 6138 injured skiers/snowboarders, 3002 uninjured controls	2000-2002	All injuries treated by Ski patrols	Age, gender, skiing ability, skiing instruction, rental equipment, helmet	Chi-square test (no OR reported)	Beginners, teenagers, females (knee), no-helmet users
Flørenes et al. (2009)	Prospective cohort study	Professional; 521 World Cup alpine skiers	2006-2008	Injuries with medical attention during training and competitions	Gender and discipline	Z-tests	Males vs. females (RR 2.05), downhill vs. slalom (RR 3.48)
Goulet et al. (1999)	Case-control	Recreational (<12 years); 41 injured skiers and 313 uninjured controls	1995-1996	All injuries treated by Ski patrols on the slopes	Binding adjustment, no ski instruction, low skill level, rented equipment	Chi-square test, Logistic regression	Low level of skill (OR 7.54), rental ski (OR 7.14), incorrect adjusted bindings (OR 2.11)
Goulet et al. (2007)	Case-control	Skiers/snowboarders (n=50593); severe injury (cases), other injuries (controls)	2001-2005	Severe injuries treated by Ski patrols on the slopes	Type of hill/terrain	Logistic regression	Snow-parks (adjusted OR 1.36) for skiers
Greenwald & Toelcke (1997)	Case-control	Recreational (n=1711); specific knee injured skiers (cases), other knee injured skiers (controls)	1992-1995	Knee injuries treated at a ski area base clinic	Gender, age, type of knee injury and severity, self-rated ability, self-rated direction of fall, binding release	Multivariate analyses (no OR reported)	For ACL injuries: Females and lack of binding release

Langran & Selvaraj (2004)	Case-control	Skiers/snowboarders; 2124 injury reports, 1782 uninjured controls	1999-2002	Injuries treated by ski patrols or medical staff at a local clinic	Risk factors for first-day participants (381 cases and 144 controls were identified)	Univariate and multivariate analyses	Snowboarding (OR 1.83), instruction (OR 2.81), rented equipment (OR 7.96)
Raschner et al. (2012)	Retrospective cohort study	Professional; 370 skiers at a Skigymnasium in Austria	1996-2006	ACL total tear	Internal risk factors related to physical fitness (exposure data missing)	T-test, Z-score test, Multivariate logistic regression	Females (RR 2.3), core strength (OR 0.26-0.54)
Ruedl et al. (2009b)	Case-control	Recreational; 93 injured skiers, 93 uninjured controls	2006-2008	ACL injury among females treated at medical staff clinic	Oral contraceptive use and menstrual cycle phase	T-test, Chi-square test	Prevulatory vs. postovulatory phase (OR 1.92)
Ruedl et al. (2011b)	Case-Control	Recreational; 93 injured skiers, 93 uninjured controls	2006-2008	ACL injuries in females	Potential intrinsic and extrinsic risk factors	T-test, Chi-square test Multivariate logistic regression	Icy terrain (OR 24.33), snowfall (OR 16.63), traditional skis (OR 10.49, prevulatory phase (OR 2.59)
Ruedl et al. (2012b)	Retrospective cohort study	Recreational skiers; 128 females and 65 males	2009-2011	ACL total tear treated in two ski injury clinics	Leg dominance in females vs. males	T-test, Chi-square test Multivariate logistic regression	Non-dominant leg for females vs. males (OR 2.0)
Shealy & Ettlinger (1996)	Case-Control	Skiers/snowboarders; 23 011 injury reports, 2573 uninjured controls	1988-1990	All injuries treated by ski patrols	Gender-related risk of injury	Not reported	Females for knee injury (OR 1.90) and males for shoulder injury (OR 2.29)
Spörri et al. (2012)	Qualitative study	Professional; WC alpine skiers		Severe injuries (absence > 28 days)	Factors related to the athlete, course, equipment and snow	Descriptive statistics	Ski-binding-plate-boot, snow conditions, physical aspects, speed and course setting
Sulheim et al. (2011)	Case-Control	Skiers/snowboarders; 3277 injury reports, 2992 uninjured controls	2002	All injuries treated by the ski patrols	Age, gender, nationality, skill level, equipment, helmet, ski school, rented equipment	Multivariate logistic regression analysis	Beginners (OR 2.72), children (OR 1.72), adolescent (OR 2.16), non-Nordic skiers (OR 1.80).
Viola et al. (1999)	Retrospective cohort study	Injuries among 7155 ski patrols/instructors	1991-1997	ACL total tear (grade III)	Gender-related risk of injury	T-test, Chi-square test	No gender-related risk of ACL injury
Westin et al. (2012)	Prospective cohort study	Professional; 431 skiers attending Swedish Ski High schools	2006-2011	Injuries with absence ≥ one day from training	Gender-related risk of injury	T-test, Chi-square test (no RR reported)	Males (hand/finger), no gender-related risk of injury overall, left leg

Injury mechanisms

A complete description of the mechanisms for a particular injury type should include aspects of the specific sport situation, the specific athlete‘s behaviour and movement, as well as detailed biomechanical characteristics of anatomical structures (Bahr & Krosshaug, 2005). In recreational alpine skiing, these descriptions are mainly based on self-reports by injured skiers in combination with post-injury clinical findings, and the information has been extracted from ski patrol reports, hospital medical reports and national trauma registries (Jarvinen et al., 1994; Kocher et al., 1998; Hunter, 1999; Hagel, 2005). Thus, the mechanisms are most often limited to specific characteristics of the skiing situation and the skier behaviour concerning injuries to the most frequently injured body parts i.e. knee, head, spine, shoulder and thumb. However, mechanisms of ACL injury are described in more detail, based on biomechanical studies and video recordings of a few real injury situations. Advantages and limitations of the different methodological approaches will be discussed later in this thesis.

Mechanisms of injury in competitive alpine skiing are unknown. There are only a few case-reports available concerning the ACL injuries. Available studies on injury mechanisms in alpine skiing, mainly among recreational skiers, are shown in Table 3 for injuries to the head/back, shoulder and thumb and Table 4 for the knee/ACL injuries.

Head and spine injuries

Reviews on injuries in recreational skiing and snowboarding have reported that head and spine injuries mainly occur as a result of falls or by collisions with other skiers or objects on the slope (Koehle et al., 2002; Boden & Prior, 2005; Ackery et al., 2007). Epidemiological studies have revealed that the most severe head and spine injuries occur first of all in collisions with immobile objects, such as trees and lift towers (Oh & Ruedi, 1982; Myles et al., 1992; Furrer et al., 1995; McBeth et al., 2009; Ruedl et al., 2011a), or in terrain parks as a result of falls during acrobatic maneuvers (Greve et al., 2009).

A study from Australia suggested that injuries to the head and spine involve different biomechanics (Siu et al., 2004). They hypothesized that the predominant pathophysiology for head injuries was deceleration impact during collisions, while injuries to the spine were most frequently caused by forwards falls or while jumping, which can result in excessive loading to the spine in all directions. This hypothesis is supported by two previous studies from Japan (Fukuda et al., 2001) and Canada (Tarazi et al., 1999).

Shoulder injuries

Two reviews on shoulder injuries have reported that falls are the most common mechanism of injury to the shoulder complex in alpine skiing (Kocher et al., 1998; McCall & Safran, 2009). Of 393 shoulder injuries reported from three seasons (1990-1993) in the US, 94% resulted from falls (Kocher & Feagin, 1996). Weaver et al. (1987) described the mechanisms of shoulder injuries (n=135) in more detail. A rotator cuff tear (n=27) was usually a result from a direct fall on the arm, while all acromioclavicular separations (n=24) were described as a direct fall on the shoulder. The most frequent injury to the shoulder complex, an anterior dislocation (n=70), was also a result from a direct fall on the shoulder, or a hyperabduction external rotation force caused by an axial load from a fall on an out-stretched arm or in a Pole-Planting situation (Weaver, 1987).

The Pole-Planting situation is described as an abduction-external rotation torque applied to the shoulder by the ski pole pulling the arm back, as the skier moves past the arm on the hill (Kocher et al., 1998; McCall & Safran, 2009). This may happen when the skier has a fixed ski pole in the hand when falling. The pole acts as an extension of the upper extremity to increase the lever arm and make dislocation of the shoulder much easier. The poles can also be caught by any number of objects to create a sudden jerking force on the shoulder.

The Skier's Thumb

It is suggested that the Skier‘s Thumb occurs when a skier during a fall holds on to the ski pole until the last moment before the hand hits the ground (Browne et al., 1976; Engkvist et al., 1982). The handle of the ski pole acts as a fulcrum at the thumb base, causing traumatic hyperabduction and extension of the metacarpophalangeal joint that injures the ulnar collaterale ligament (Browne et al., 1976; Chuter et al., 2009). This is supported by a review on clinical studies describing magnetic resonance image (MRI) findings from skiing injuries (Boutin & Fritz, 2005).

In the study by Engkvist et al. (1982), video recordings from six WC competitions during the 1979/1980 winter season were reviewed in order to find out whether their statement was relevant. In total, 14 falls were analyzed, and the skier kept the pole in his hand until it hit the ground in all these cases. The authors reported that these observations supported their theory of the injury mechanism.

Table 3. Articles on injury mechanisms in alpine recreational skiing

Reference (publ. year), country	Study period	Population	Methodological approach	Outcome (mechanism)
Head/Spine				
Fukuda et al. (2001), Japan	1994-1999	Skiers (n=442)/ snowboarders (n=634)	Hospital examinations of head injury	Skiers: Falls (55%), collisions (42.5%), jumps (2.5%)
Greve at al. (2009), USA	2002-2004	Skiers (n=533)/ snowboarders (n=473), others (n=7)	Emergency medical center reports of head injury	All: Falls (74.1%), collisions with fixed objects (13.1%), collisions with other skier (10%), other (2.7%).
Oh et al. (1982), Switzerland	1974-1981	Recreational skiers (n=57)	Clinical examinations and laboratory experiment of depressed skull fracture	Collisions with obstacles (54.4%), other skier or skier equipment. Temporal injury occurs at energy > 1-2 kN
Siu at al. (2004), Australia	1994-2002	Skiers (n=51)/ snowboarders (n=35)/ others (n=5)	Hospital reports of injury to the head (n=25) or spine (n=66)	Skiers: Falls (47%), jumps (31%), collisions (20%), other (2%)
Tarazi et al. (1999), Canada	1994-1996	Skiers (n=34)/ snowboarders (n=22)	National Trauma Registry combined with medical and ski patrol reports of severe spinal injury	Skiers: Falls (59%), jumps (2%), chairlifts (15%), collisions (6%)
Severe injuries				
Furrer et al. (1995), Switzerland	1984-1992	Recreational skiers (n=361)	Hospital reports of severe injury	Falls (65.9%), collisions with obstacles/objects (32.4%), caught by an avalanche (1.7%)
McBeth et al. (2009), Canada	1996-2006	Skiers (n=111)/ snowboarders (n=85)	Trauma registry of major traumatic injuries (Injury Severity Score ≥ 12)	Skiers: Falls (44.1%), collisions (47.7%), jumps (7.2%), caught by an avalanche (0.9%)
Myles et al. (1992), Canada	1983-1988	Recreational skiers (n=145)	Hospital reports of injury to the nervous system (head) or spine	Isolated falls without collision (48%), collisions (41%); with trees (23%), other skier (6%), fences (5%), lift equipment (3%). Fall from lift (2%), other (6%) and unknown (3%).
Ruedl et al. (2011a), Austria	2005-2010	Recreational skiers (n=207, including eight snowboarders)	National register of fatal injuries	Traumatic deaths (n=97): Fall (41.2%), impact with solid object (35.1%), collisions with other skier (18.6%), avalanche on slope (4.1%), unknown (1%)

Shoulder				
Kocher et al. (1996), USA	1990-1993	Recreational skiers (n=3247)	Ski resort clinic medical reports of shoulder injury (n=393)	Falls (93.9%), collisions with skiers (2.8%), Pole-Planting (2.3%), collisions with trees (1%)
Weaver (1987), USA	1978-1979	Recreational skiers (n=135)	Clinical reports and follow-up questionnaires of shoulder injury	Anterior dislocation: Hyperabduction/external rotation force (60%, incl. Pole-Planting 24%), direct fall on the shoulder (40%). Rotator cuff: Falls on an abducted arm (90%). Acromioclavicular: Mainly direct fall on the shoulder.
Thumb				
Brown (1976), USA	3 years	Recreational skiers (n=12)	Clinical reports and ssurgical findings of injury to the MCP joint (Skier's Thumb)	Surgical findings: Intra-articular fracture (n=3), soft tissue instability (n=9)
Chuter et al. (2009), Great Britain	10 years	The public (n=127); skiers (2.4%)	Clinical reports of UCL repair to the thumb	All: Mainly falls leading to extension/abduction of the MCP joint (66%)
Engkvist et al. (1982), Sweden	1979-1980	Recreational skiers (n=133)	Emergency clinical and hospital reports and follow-up questionnaires of thumb injury (n=126)	Fall directions: Forward (86.5%), to either side (15.9%), backward (10.3%), missing data (13.5%) UCL-MCP/Skier's Thumb (71%)

Knee/ACL injuries

As described previously, ACL injury is the most frequent injury type in recreational, as well as in professional alpine skiing. The ACL is an intracapsular extrasynovial ligament of the knee, which is important for knee stabilization during sport activities (Kam et al., 2010). The entire ACL is on average 32 mm long from the femoral origin to the tibial insertion. The ligament is attached proximally at the posteriomedial aspect of the lateral femoral condyle and inserts distally at the anterior part of the medial intercondylar spine of the tibia. The ACL is distinguished into two functional groups of fibers; the anteriomedial (AM) and the posteriolateral (PL) bundles (named with regard to their insertion on the tibia) (Kopf et al., 2009). The ACL has been documented to be a primary restraint to anterior displacement of the tibia relative to the femur and a secondary restraint to internal tibial rotation and varus-valgus angulations (Kam et al., 2010).

The Phantom Foot injury

The Phantom Foot is claimed to be the most common mechanism for ACL injuries in recreational skiing based on retrospective interviews of injured skiers and qualitative video analysis of 10 ACL injury cases (Ettlinger et al., 1995; Natri et al., 1999). In this situation, the skier is out of balance backwards with the hips below the knees (Figure 7). The uphill arm is back, and the upper body 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". This is supported by a biomechanical study of Hame et al. (2002), who 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. Knee extension in combination with internal rotation of the tibia was also suggested as a mechanism in a case report, based on interview and arthroscopy of an isolated ACL tear (Kennedy et al., 1974). In addition, internal rotation of the knee was suggested to be a key factor in an ACL injury suffered by a WC downhill skier, based on a 3-dimensional kinematic reconstruction of the knee joint at the time of injury (Krosshaug et al., 2007b). 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.

The Boot-Induced Anterior Drawer

Another mechanism described among recreational skiers, is the so-called Boot-Induced Anterior Drawer (BIAD). The BIAD mechanism has been described as a situation where the skier loses balance backwards while jumping and lands on the ski tails with almost extended knees (Ettlinger et al., 1995; Tecklenburg et al., 2007) (Figure 7). 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. However, studies have suggested several loading conditions which can contribute to ACL injury while landing from a jump, not only 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 due to the BIAD in combination with tibiofemoral compression load (Ettlinger et al., 1995; Yeow et al., 2010). Another suggested mechanism that may generate anterior tibial drawer in this situation is a decreased activation of hamstrings compared to quadriceps. This theory is based on electromyography (EMG) and kinematics of an accidental ACL injury suffered by a professional racer under experimental conditions (Barone et al., 1999).

Further, previous studies have 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, 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 (McConkey, 1986; Geyer & Wirth, 1991; Gerritsen et al., 1996; DeMorat et al., 2004). However, the literature regarding quadriceps contribution to ACL failure is controversial (Gerritsen et al., 1996; Aune et al., 1997; Markolf et al., 2004; Yu & Garrett, 2007). 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 (Hame et al., 2002). Hyperflexion was also reported as a mechanism of an isolated ACL tear in a case report of an expert skier passing a small bump on the course (Ekeland & Thoresen, 1987).

Valgus-external rotation

In addition to the Phantom Foot and the BIAD, valgus-external rotation has been described as a common mechanism of ACL injury in recreational skiing (Figure 7). This situation occurs when the skier falls forward while catching the snow with the tip of the ski (Jarvinen et al., 1994). The ski will then rotate outwards, forcing the knee into tibia external rotation and valgus. According to two reviews on knee injuries in skiing, this situation is believed to lead primarily to a MCL injury, but has also been seen to involve ACL injury in approximately 20% of the cases (Howe & Johnson, 1982; Johnson & Ettlinger, 1982). However, this forward twisting fall is suggested to have become the dominant ACL injury mechanism in recreational skiing since the introduction of carving skis (Ruedl et al., 2009a; Ruedl et al., 2011c). It is assumed that the shorter tail of the carving skis compared to the traditional skis has caused a change in the distribution of ACL injury mechanisms from the backward twisting fall ("Phantom Foot"/valgus-internal rotation) to the forward twisting fall (valgus-external rotation), contributing to the decrease in ACL injury risk reported from 1992 to 2006 (Johnson et al., 2009). However, this change in the distribution of injury mechanisms is only based on retrospective questionnaires of injured skiers and should therefore be interpreted with caution.

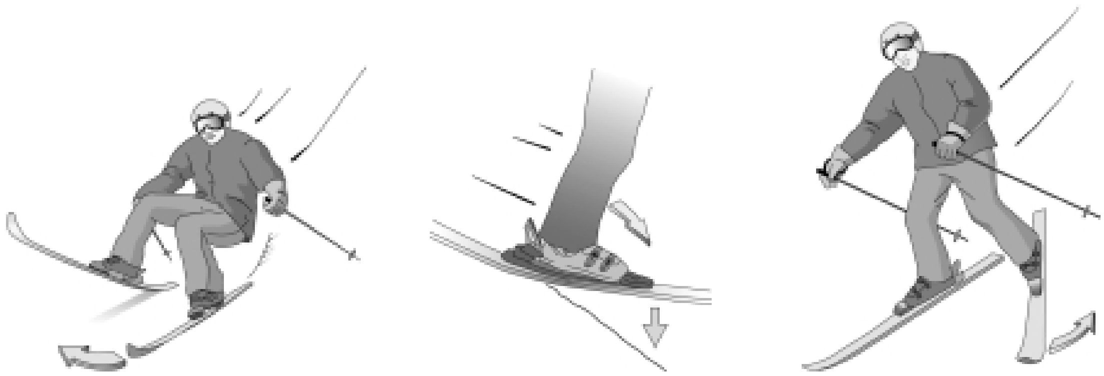

Figure 7. Common mechanisms of ACL injury among recreational skiers. From left to right: (a) "Phantom Foot" mechanism; (b) BIAD; and (c) valgus-external rotation. The figure is retrieved from Koehle et al., 2002. Permission to reproduce has been received from Emma Pearl, Sport Medicine, 2008.

Even though the suggested ACL injury mechanisms have been described among recreational skiers, we do not know to what extent these descriptions appear among competitive skiers, as professional ski racing requires extreme skiing skills, experience and fitness, as well as more aggressive equipment. The skiing conditions and the terrain are also obviously more challenging. Thus, one aim of this thesis was to describe the ACL injury mechanisms in detail among competitive alpine skiers.

Table 4. Articles on ACL injury mechanisms in alpine skiing

Reference (publ. year), country	Population	Type of ACL injury	Methodological approach	Outcome (mechanism)
Observational studies				
Ekeland et al. (1987), Norway	Expert skier (n=1)	Isolated ACL tear	Interview and video recording	Weighted hyperflexion of the knee prior to falling
Ettlinger et al. (1995), USA	Recreational skiers (n=1400)	ACL sprain	Interview + video of 10 cases (incl. nine ski racers) (22 years)	From video analysis: Phantom Foot (n=5), BIAD (n=4), unsure (n=1) From interviews: Phantom Foot, BIAD, valgus/ER, hyperextension and collision
Feagin et al. (1987), USA	Expert skiers (n=2)	Two case reports of ACL tear	Interview and arthroscopy	While skiing without fall
Fischer et al. (1994), Switzerland	Recreational skiers (n=6)	ACL rupture or avulsion	Interview and arthroscopy	Six different loading mechanisms without binding release were supposed: (1) ER/valgus at knee flexion > 90° (2) ER/valgus at knee flexion > 120° + anterior drawer loads (3) IR at knee flexion > 120 ° + anterior rawer loads (4) IR/valgus at knee flexion < 30 ° + anterior drawer loads (5) ER at knee flexion of 100° + anterior drawer loads (6) IR/valgus at flexion approx. 90°
Friden et al. (1995), Sweden	Participants in recreational sports (n=100); alpine skiers (n=30)	Total ACL rupture	Interview and arthroscopy	Skiers: 22 of 30 reported no-weight bearing at the time of injury → supposed tearing force and "distraction" injuries
Geyer et al. (1991), Germany	Ski racer (n=1)	Isolated ACL tear	Video and arthroscopy (1986/87)	Quadriceps contraction in landing after a jump in a backward position (without falling) → anterior drawer of tibia relative to femur
Jarvinene et al. (1994), Finland	Recreational skiers (n=51); alpine skiers (n=32)	ACL rupture	Questionnaire and arthroscopy (1980-1989)	Skiers: Valgus/ER (n=14), flexion/IR (Phantom Foot) (n=14), other (n=4)
Kennedy et al. (1974), Canada	Recreational skiers (n=1)	Case-report of an isolated ACL tear	Interview and arthroscopy	IR of tibia at knee flexion 15-20°
Krosshaug et al. (2007b), Norway	Ski racer (n=1)	ACL tear	Video analysis/MBIM technique	"Wide snow plow " mechanism; IR/valgus at knee flexion approx. 65°

Marshall et al. (1975), USA	Recreational skiers (n=24)	Knee ligament injury	Interview and MRI	Valgus/ER
McConkey (1986), Canada	Experts and ski racers (n=13)	ACL rupture	Interview + video of two cases (1981-1985)	A combination of BIAD and Quadriceps contraction. No binding release (n=13). Without fall (n=5). Recovery from a falling back position (n=9), landing from a jump (n=4)
Ruedl et al. (2009a), Austria	Recreational skiers (n=65)	ACL injury among female carving skiers	Questionnaires (2007/08)	Forward twisting fall (valgus/ER) (51%) versus backward twisting fall (Phantom Foot) (29%)
Ruedl et al. (2011c), Austria	Recreational skiers (n=220)	ACL partial or total tear among females (n=161) and males (n=59)	Questionnaires (2008-2010)	Forward twisting fall (valgus/ER) (54%) versus backward twisting fall (Phantom Foot) (29%)
Sanchis-Alfonso et al. (2000), Spain	Novice recreational skier (n=1)	A case report of a bilateral ACL tear	Interview and X-ray/MRI	Phantom Foot bilaterally
Tecklenburg et al. (2007), Austria	Ski racer (n=1)	A case report of an ACL tear	Interview and video	Landing from a jump; BIAD in combination with ER
Urabe et al. (2002), Japan	Recreational skiers (n=80)	ACL injury among females (n=37) and males (n=43)	Questionnaires (1995-1997)	While falling down (55%), prior to falling (21%), after falling (24%). No binding release at the time of accident (96%)
Clinical studies				
Paletta et al. (1992), USA	Recreational sports (n=150); skiers (n=75)	ACL tear	Interview and arthroscopy (medical reports) (1987-1989)	Skiers: ER/valgus ("ski tip out") (32%), IR/valgus ("ski tip in") (27%), knee flexion and quadriceps contraction (15%), hyperextension (13%), unknown (13%). Associated meniscal injury (n=31): Lateral meniscus (74%), medical meniscus (19%), both (6%). Mainly located to the posterior horn.
Speer et al. (1995), USA	Recreational skiers (n=42)	ACL tear	Interview and MRI (1988-1992)	Suggested that valgus force is an important component of the ACL mechanism in skiing, based on associated bone bruise (osseous injury detected on MRI): Lateral femur condyle (40%), medical femur condyle (10%), lateral tibia plateau (81%), medical tibia plateau (29%).
Biomechanical studies				
Aune et al. (1995), Norway	Recreational (n=2)	Motion pattern and muscle activity during the landing phase after a jump	Motion analysis on the slope	Due to the knee flexion angle, the suggested mechanism of an ACL injury was a combination of BIAD, knee hyperflexion and absence of protecting hamstrings force, rather than a quadriceps contraction

Aune et al. (1997), Norway	Cadaveric human knees (n=6)	Anterior share force at ACL failure	In vitro	Maximal anterior share force induced by a maximum quadriceps contraction at 30° knee flexion was minimal (< 89 N). Quadriceps contraction causes a compressive joint force, which resist anterior tibial translation.
Bally (1989), Switzerland		Loads on the ACL at the impact and rotation phase	Computer simulation of a typical BIAD situation	The ACL loads increase with slope steepness and boot stiffness.
Barone et al. (1999), Germany	Expert (n=1)	Knee kinematics and kinetics of an ACL injury in a backward fall after landing	Motion analysis on slope	Combination of BIAD and less hamstrings activation was suggested as the ACL injury mechanism.
Gerritsen et al. (1996), Austria	Not applicable	ACL forces under a simulated backward fall during landing after a jump	Computer simulation	In a recovery situation, the ACL forces are mainly caused by external forces (75%), and to a less degrees quadriceps contraction (25%).
Hame et al. (2002), USA	Cadaveric human knees (n=37)	ACL forces with application of tibial internal and external torques	In vitro	IR at fully flexed or extended knee caused the highest ACL resultant forces, representing the most dangerous loading condition for injury form twisting falls during skiing.
Koyanagi et al. (2006), Japan	Recreational skiers (n=10)	Joint moments, muscle activity and forces induced by the boot in different skiing posture	Motion analysis in lab	A combination of BIAD and quadriceps contraction may contribute to an ACL injury in a backward bending posture while skiing.
St-Onge et al. (2004), Canada	Not applicable	ACL strain under simulated Phantom Foot conditions	Computer simulation	A binding with 2-pivot points (in front and back of the center of the boot), could sense twist loads applied to the ski both at the front and the back. This may probably reduce the occurrence of ACL injuries.
Webster & Brown (1996), Great Britain	Not applicable	ACL loads under simulated BIAD conditions	Computer simulation	The anterior sharing force of the knee increased with (1) increasing velocity of the skier, (2) increasing stiffness of the ski, boot and binding, and (3) decreasing the slope of the landing area.
Yeow et al. (2010), Austria	Cadaveric porcine knees (n=12)	Contribution of axial impact compression load to ACL load during simulated ski landing impact	In vitro	Linear relationship between axial compression load and anterior tibial load. The generated peak anterior tibial load was 16% of the applied axial compression load, due to the tibial plateau angle.

Methodological approaches to injury mechanism research

Different methodological approaches are used to describe the mechanisms of injury in sports (Krosshaug et al., 2005; Yu & Garrett, 2007; Renstrom et al., 2008; Shimokochi & Shultz, 2008; Quatman & Hewett, 2009; Quatman et al., 2009; Quatman et al., 2010) (Figure 8). In alpine skiing, observational approaches (retrospective interview and video analysis) have mainly been used to describe the inciting event in terms of the injury situation and skier‘s behavior, while biomechanical studies (*in vitro*, motion analysis and mathematical simulation) have provided information about joint kinematics and kinetics. Both observational and biomechanical approaches have contributed to increasing our understanding of how the injuries occur. However, there are some advantages and limitations of the different approaches, which we should be aware. To better illustrate these methodological considerations, available studies on ACL injury mechanisms in alpine skiing, will be used as examples in the following sections (Table 4).

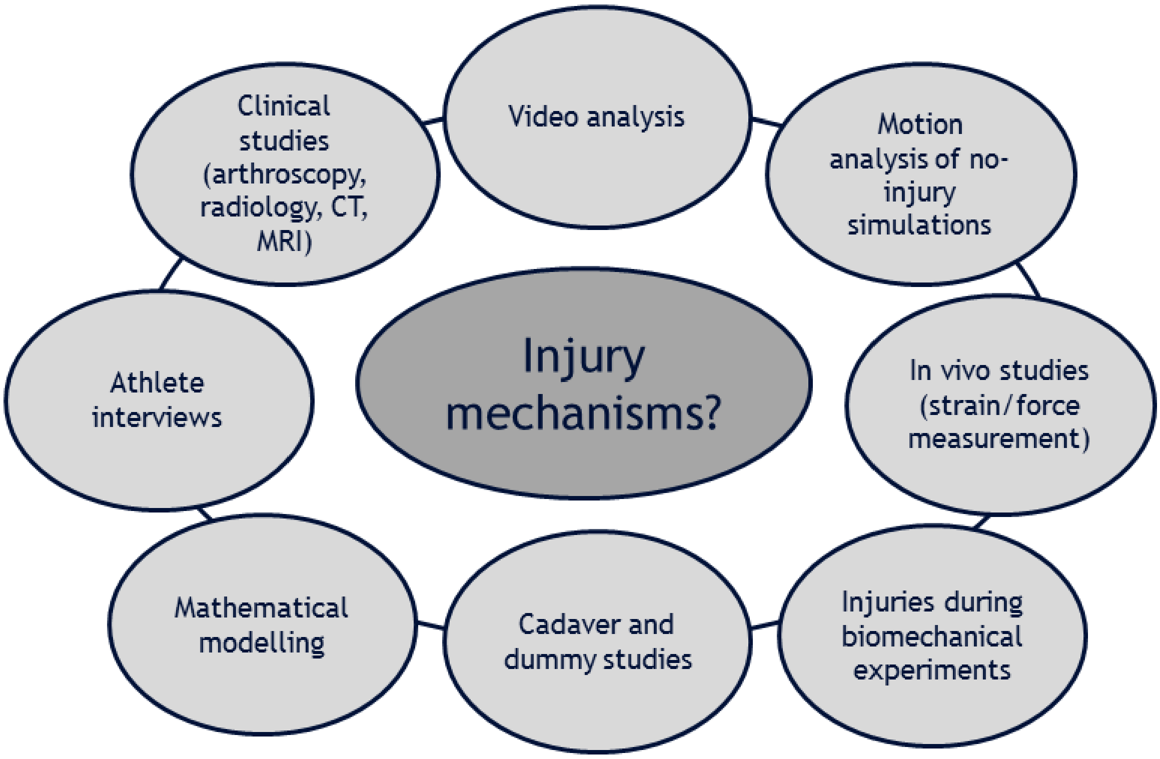

Figure 8. Research approaches to describe the injury mechanisms in sports. The figure is taken from Krosshaug et al., 2005 and reproduced with permission from Tron Krosshaug, 2012.

Retrospective interview and questionnaire

Retrospective interviews and questionnaire are the most commonly used approach to study injury mechanisms in sports (Krosshaug et al., 2005; Shimokochi & Shultz, 2008). Using this approach, it may be possible to describe the inciting event preceding the injury, at the time of injury, as well as after the injury. It is relatively easy to obtain data through a personal interview or a questionnaire with the injured athlete or witnesses to the accident. However, the descriptions of the injury mechanisms are most often limited to the terms of the specific sport situation and the athlete‘s behavior.

In alpine skiing, most of the ACL injuries among recreational skiers are reported to occur during falling without or before binding release (Marshall et al., 1975; Fischer et al., 1994; Ruedl et al., 2009a). However, interviews may be influenced by the simple fact that these injuries may happen at such high speed that the skier may not even be able to describe what took place. In addition, many skiing falls and collisions are not reportable because there may be much confusion involved at the time of accident. A study reported that it was difficult for the skiers to state whether they were weight-bearing/falling or not at the time of injury (Friden et al., 1995), and another study reported that the skiers had challenges to state whether the injury occurred before or after binding release (Urabe et al., 2002). In injury situations without falling, the circumstances surrounding the injury may be more controlled, thus these descriptions are often more precise. It is not unusual that experienced skiers report a sensation of a "pop" or a feeling of "giving way" within the knee during an ACL injury situation (McConkey, 1986; Fischer et al., 1994; Bianco et al., 1999).

Another limitation with retrospective interviews and questionnaire is that the information may be influenced by recall bias. Information gained about the mechanism of injury depends on the skier‘s ability to recall the event. With a long period between injury and the time of interview, it could be questioned whether the skiers are able to recall the exact mechanisms. Some studies have not reported how long time after injury the skier was interviewed or the questionnaire was completed, which may be critical for the results (Urabe et al., 2002). In addition, it is not possible to know whether the description is actually the injured skier‘s interpretation of the event, or if the description is influenced by what he/she has been told by witnesses on the slope or other people involved in the situation. Further, selection bias may appear if not all invited skiers want to participate in the study or not all participants respond the questionnaire. In other words, it is important that the samples are representative for the population (Urabe et al., 2002; Ruedl et al., 2009a).

A challenge with the interview approach is the use of definitions, categories and variables in the injury report/questionnaire. It is critical that the pre-defined categories used are representative for the actual ACL mechanisms. We should also keep in mind that it may be challenging for the injured skiers to place themselves into predefined categories. Some studies have categorized the mechanisms according to whether the ski tip went out or in during the fall (Marshall et al., 1975; Paletta et al., 1992). "Ski tip went out" was interpreted as external rotation with moderate to extreme flexion, while "Ski tip went in" was interpreted as internal rotation with extension or slight flexion. ACL injury mechanisms have also been categorized according to whether the skier fell forward or backward (Ruedl et al., 2009a; Ruedl et al., 2011c). A forward twisted fall was interpreted as knee valgus-external rotation, while a backward twisted fall was interpreted as knee flexion-internal rotation.

Reported kinematic data are often the authors' interpretation of the skiers' description concerning the injury situation (Jarvinen et al., 1994; Sanchis-Alfonso & Tinto-Pedrerol, 2000). Kinematics and kinetics of the knee joint, as well as ACL force and strain, cannot be determined from athlete interviews or questionnaires. Thus, detailed information regarding the injury mechanism, based on these approaches, should be interpreted with caution (Feagin et al., 1987).

Clinical studies

To better understand the mechanisms of ACL injury, it is possible to analyze the pathology of the injury and associated damages to the knee by using radiography, MRI or arthroscopy. These techniques can give detailed information about injuries to the meniscus, collateral ligaments, localized cartilage injury and bone bruise. Two reviews on MRI of skiing injuries have reported that MCL injury is frequently associated with ACL tear, caused by forced knee valgus when falling from a snowplow position or while catching an edge (Boutin & Fritz, 2005; Kam et al., 2010).

Speer et al., (1995) investigated the incidence and pattern of bone bruises demonstrated on MRI among 42 ACL injured skiers. The location of these osseous lesions can be used to speculate about injury mechanisms and directions of forces. MRI examinations were combined with a standard knee injury questionnaire to obtain the patients' description of the injury mechanisms. The study found that 40% of the knees had bone bruises on the lateral femur condyle, and 81% in the posterior lateral tibia plateau. The pattern of bone bruises was different from those observed among non-skiing athletes. The study concluded that skiing-related ACL tears seem to occur with more knee flexion, for example during a backward fall.

Clinical techniques do not directly analyze injury mechanisms, as these studies are not able to describe the actual event leading to the findings and detailed joint biomechanics. We cannot know whether the damage occurs before, during, or as a result of the ACL tear. However, clinical examinations can be used to support or contradict observations from other methods, such as interview of the injured skier and video analysis of the incident (Krosshaug et al., 2005).

Video analysis

By utilizing video recordings, it is possible to obtain more detailed information on what took place when the injury occurred than by retrospective interviews and questionnaires (McConkey, 1986; Fischer et al., 1994). It is also possible to compare injury versus no-injury situations by analyzing videotapes of matched controls. When distinguishing between injury and no-injury situations, it may be possible to identify critical characteristics of the injury mechanisms (Meeuwisse, 2009).

Ettlinger et al. (1995) conducted one of the first studies investigating injury mechanisms in sports utilizing video analysis. They analysed 10 videos of ACL injuries among recreational skiers, which they thought were representative for the 1,400 injury reports they evaluated. They identified the Phantom Foot mechanism and the BIAD mechanism, which have been shown to be two common injury mechanisms in recreational skiing.

Even though visual analysis of injury mechanisms is a convincing exercise, where remarkably consistent patterns can often be readily identified, there are some limitations of this method of which one should be aware (Krosshaug et al., 2005; Koga et al., 2010). We cannot in all cases be sure of the exact time of injury. There may be more than one plausible injury time point, especially in situations of crashes. Another limitation is that we cannot be sure whether the observations of joint angles and body motions are, in fact, the mechanisms leading to the ACL injury, and not a result of the injury. It has also been documented that visual 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 (Krosshaug et al., 2007a).

To obtain more precise estimates of knee kinematics in real ACL injury situations, Krosshaug & Bahr (2005) developed the MBIM technique to reconstruct injury mechanisms from video sequences with uncalibrated cameras. This technique involves a manual matching of a skeleton model to the background video pictures. 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 (Koga et al., 2010). In alpine skiing, this technique has so far been used for only one injury case, describing the "wide snow plow" mechanism to a WC downhill skier (Krosshaug et al., 2007b). Internal rotation and valgus of the knee was suggested to be a key factor of the ACL injury, based on a three-dimensional reconstruction of knee joint kinematics.

A challenge with the MBIM technique is that good resolution of the video is necessary, as well as at least two camera views where the injured knee is shown clearly from different angles. In addition, anthropometrical measures of the skier are needed to reconstruct the skier‘s motion three-dimensionally. Exact measurements of the skis and boots used by the skier, as well as reference points in the environment, would also be helpful to reconstruct the motion even more accurately. In addition, the matching process is very time consuming, and the estimated time to match the model to the background video pictures is 1-2 months (Krosshaug & Bahr, 2005).

Biomechanical motion analysis

Motion analysis can estimate biomechanical variables much more precisely than what is possible with analysis of video recordings. Knee joint kinematics and kinetics associated with an ACL injury can be estimated during high risk maneuvers in the laboratory, while motion pattern and muscle activity during sport specific performance can be measured on the slope.

In the study by Barone et al. (1999), the researcher intended to perform motion analysis of downhill ski racers on the slope to subsequently simulate the BIAD mechanism in the laboratory. The researchers observed approximately 250 landing situations after a jump and obtained joint kinetics and kinematics to the skiers by using EMG and video recordings. Unfortunately, a skier accidentally torn his ACL during one of the landing situation, characterized as a BIAD injury. The researchers could then give a description of the BIAD mechanism with both observational and biomechanical approaches. However, injury during experimental studies is rare and undesired.

Among elite ski racers on-slope, motion pattern and muscle activity in lower extremities were examined during jumping-landing in downhill skiing (Aune et al., 1995). Muscle contraction of the knee flexors and extensors related to the backward fall mechanism of ACL injury was studied by EMG and video analysis. The study reported that the knee flexors were recruited before touchdown and a mean of 60 ms earlier than the extensors. The mean knee flexion angle at the instant of landing was 36°. As the landing was stabilized, the extensor activity persisted during eccentric work. The knee was flexed substantially as the extensors became the dominating muscles. Similar pattern of muscle activity in a backward leaning position was reported in a study performed in the laboratory (Koyanagi et al., 2006). However, the quadriceps ability to apply an anterior drawer force able to rupture the ACL is still questioned.

It is unsure to which extent circumstances in motion analysis studies differ from real injury situations. A limitation of biomechanical motion analysis is that we cannot really know if the observed mechanics expose the athletes to increased risk of injury. Motion analyses are unable to estimate ACL tensile force and strain (change in length of the ligament from its initial length under loading conditions), without combining them with more detailed biomechanical approaches, such as *in vitro* studies and mathematical simulations.

In vitro studies

Several biomechanical methods have been used to describe tensile force and strain within the ligament. *In vitro* studies describe investigations preformed in a laboratory, using isolated tissues, such as cadaver knees. *In vitro* studies can measure ACL tensile forces and strain values under application of external loads which are likely to be involved in ACL injury mechanisms. One *in vitro* method is to use a force transducer or strain-gauge attached to the ACL to directly measure the amount of ACL tensile force or strain when different loads are applied to the knee (Krosshaug et al., 2005; Shimokochi & Shultz, 2008; Renstrom et al., 2008). To gain a better understanding of the mechanism of ACL injury during alpine skiing, Hame et al. (2002) investigated the forces generated in the ACL with application of tibial loading to 37 cadaveric knees at different flexion angles. A load cell that measured resultant force in the ligament was attached to the tibial insertion of the ACL. The result of this study showed that the highest mean ACL force was generated with application of 10 Nm internal tibial torque to a hyperflexed (243 N) or fully extended (230 N) knee. The study concluded that this result represents the most dangerous loading conditions for injury from twisting falls during skiing.

An advantage with *in vitro* studies is that an assumed injury mechanism can be reproduced by loading an intact cadaver knee joint to failure. Then it is possible to see if the mechanism produces the intended pathology. In addition, muscle forces can also be incorporated into the model. Aune et al. (1997) performed a study to investigate if a maximum quadriceps contraction was able to assist a passive anterior tibial translation to ACL rupture. Six pairs of cadaveric knees were tested at 30° of knee flexion. The knees were displaced to ACL failure by pulling the tibia anteriorly with a deformation rate of 30 mm/sec with a simultaneously applied quadriceps force. One knee of each pair was tested with 889 N quadriceps force, while the contralateral knee of each pair was used as control, tested correspondingly with only 5 N quadriceps load. This study reported that the average anterior shear force imposed by the 889 N quadriceps force, prior to failing the knees, was only 62 N. Thus, the study concluded that the compressive joint force from quadriceps contraction was able to protect the knee from an anterior tibial translation.

Although *in vitro* studies have provided significant insight into the ACL function, a challenge of this methodological approach is that a valid simulation of real injury conditions is difficult to perform *in vitro*. There are several factors which may be critical for the ACL responses and the results, e.g. the use of different testing machines, the magnitude as well as the direction and velocity of the applied loads, and the type and age of the cadaver knees. This may reflect the huge controvercity in the literature regarding whether the quadriceps muscles may contribute to ACL failure (Markolf et al., 1990; Aune et al., 1997; DeMorat et al., 2004; Markolf et al., 2004; Yeow et al., 2010).

Computer simulation

Another biomechanical method to understand ACL tensile force and strain is computer simulation models. This method has been used to calculate the amount of ACL stress based on predicted kinetics and kinematics. A computer simulated model for estimation of ACL strain in complex loading conditions was recently developed by using a combined cadaveric and analytic approach (Mizuno et al., 2009). This was the first study investigating joint mechanical contributions to ACL strain in response to dynamic three-dimensional knee loading. ACL strain was estimated for 21 external loading conditions. They found four variables which were prominent for ACL strain (1) knee flexion angle, (2) anterior shear force, (3) valgus loading and (4) internal rotation of the tibia. Further, they reported that internal rotation of the tibia in combination with either full extension or max flexion represents the most dangerous loading situation for ACL injury.

An advantage of computer simulation studies is that they make it possible to test the function of individual structure while controlling for all other structures, thus demonstrating the effects of different muscle activations on ACL loading patterns during specific sport maneuvers (Shimokochi & Shultz, 2008). Another advantage is that injury mechanisms or injury risk situations can be studied without any hazard to the relevant population. Several studies have developed models for simulating ACL injury mechanisms while skiing (Bally et al., 1989; Gerritsen et al., 1996; Webster & Brown, 1996). Gerritsen et al. (1996) developed a computer simulation model of a downhill skier and the interaction between the model and the snow surface. The aim was to simulate the ACL loads during landing after a jump, including recovery movement and the contribution of quadriceps muscle force. Kinematic input was obtained from video recordings of downhill racers in the 1994 Olympics in Lillehammer. The study observed a peak ACL shear force of 1350 N during the recovery movement at 66° of knee flexion. They assumed that 75% of the ACL shear force was caused by external loads, while 25% was caused by a contraction of the quadriceps muscles.

One limitation of computer simulation studies is that the models are simplified, and the extent to which the calculated values from these studies reflect actual values during real skiing situations is unknown (Shimokochi & Shultz, 2008). In the study by Gerritsen et al. (1996), the model was only made two-dimensional, hamstrings muscle force was not included and the stimulation of quadriceps muscles was constant during the entire landing phase (0.2 s). In addition, there is no consistency whether simulation studies have considered the tibia plateau slope when calculating the quadriceps induced ACL stress. Thus, the relationship between knee flexion angle and ACL load induced by quadriceps contraction is not clear. Another limitation of simulation studies, in general, is that the strain behaviour of the normal ACL in living humans (*in vivo)* is not fully explored. The strain distribution varies along the length of the ligament and is dependent on several factors e.g. the knee orientation, the direction and magnitude of the applied load and structural properties of the ligament (Beynnon & Fleming, 1998; Fleming & Beynnon, 2004).

Summary

Observational approaches, such as retrospective interview and video analysis, can describe real injury situations preceding the time of injury, at the time of injury, as well as after the injury. However, they have some methodological limitations as they are not able to describe exactly when and how the injuries occur. Biomechanical studies, such as *in vitro*, motion analysis and mathematical simulation, may increase our understanding of why and how specific injuries occur in a particular situation or motion pattern. However, these studies are based on simulation or replication of real injury situations. In conclusion, there is actually no single approach that can describe the mechanisms for a particular injury type completely, thus a combination of different approaches would appear to be the "gold standard".

Injury prevention

Alpine skiing

To prevent skiing injuries, knowledge about the magnitude of the injury problem, risk factors and injury mechanisms is needed. As there is limited knowledge on risk factors and injury mechanisms in competitive alpine skiing, there are no studies available on injury prevention. In recreational skiing, however, a few studies have focused on preventive measures related to specific characteristics of the skier, skier equipment or environmental factors (Table 5).

Two studies have shown that interventions aimed to improve the skiers' knowledge on how to avoid injuries and increase skiing safety, have significantly reduced the injury risk. Ettlinger et al. (1995) developed an experimental training program for experienced professional skiers to examine if specific awareness training could help reduce the risk of ACL injuries. During the 1993/1994 season, ski patrols and ski instructors (n=4,000) from 20 ski areas in Vermont (USA) participated in the training program. The program focused on improving psychomotor skills to develop an awareness of the events leading to ACL injury. The program was divided into three parts: 1) avoiding high-risk behaviour, 2) recognizing potentially dangerous situations, and 3) responding quickly and effectively whenever these conditions encountered. Data from 22 ski areas, where staff were not exposed to the training program, formed a control group. Data concerning ACL injuries were collected from both groups for three seasons (1991-1994), and a total of 179 severe knee ligament injuries were evaluated. During the test season (1993-1994), ACL injuries declined by 62% among the intervention group compared with the two previous seasons, while no decline occurred in the control group. The study concluded that the risk of ACL injury among experienced skiers can be reduced by awareness training.

Jørgensen et al. (1998) performed a randomized intervention study to test the effect of an instructional ski video on skiing behaviour and the risk of injury among novice recreational skiers. Danish skiers (n=763) were enrolled into two study groups, based on whether or not an instructional video had been shown in their busses on the way to skiing resorts in France. The video focused on information regarding how to ski safely and advices on how to avoid injuries. The outcome parameters, skiing behaviour and number of injuries, were registered by a questionnaire on the return back home eight days later. The study found a reduction in injury risk of 30% in the intervention group compared to no reduction in the control group, and the knee injury risk was significantly lower if the bindings had been tested and adjusted. The study concluded that information from an instructional ski video can change the skiing behaviour and reduce the risk of injury among novice recreational alpine skiers (Jørgensen et al., 1998).

Regarding equipment, there is evidence showing that helmet use reduces the risk of head injuries. A recent meta-analysis reviewing the effect of helmet use on the risk of head and neck injuries among skiers and snowboarders, reported that the risk of head injury was reduced by 35% with helmet use, based on 12 included studies (Russell et al., 2010). They also reported no significant association between helmet use and an increased risk of neck injury, and further, it is suggested no relation between helmet use and risk-taking behaviour (Hagel et al., 2005a). Ackery et al. (2007) reported in their review of traumatic injuries to the brain and spinal cord that helmets reduce the risk of head injury by 22-60%. This is based on several case-control studies that have used an uninjured group of skiers as control group and adjusted for potential confounding factors such as age, gender, equipment and skiing ability (Macnab et al., 2002; Hagel et al., 2005b; Sulheim et al., 2006). A case-control study that used skiers and snowboarders with other injuries as control group, reported that helmet use reduced the risk of head injury by 15% (Mueller et al., 2008).

Finch & Kelsall (1998) examined the extent to which alpine ski bindings have been evaluated and demonstrated to be effective in preventing injuries. The review included 15 studies of different methodological approaches, and there was only one experimental prospective study which evaluated the effect of correctly adjusted bindings (Hauser, 1989). In this study, recreational skiers were randomly assigned into an experimental group (n=460) and a control group (n=690). The experimental group had their bindings tested and adjusted professionally prior to the winter season for two years, while the control group did not. The study found that correctly adjusted bindings reduced the risk of injuries, in general, and lower extremity injuries, in particular. The injury rate of lower extremity injuries in the experimental group was 3.5 times lower than in the control group. However, Finch & Kelsall concluded in their review that the current bindings are insufficient for the multidirectional release required to reduce the risk of serious knee injuries. Thus, they suggested that further technical developments and innovations of binding design, mounting and adjustment are required.

Regarding preventive measures related to the skiing environment, only one study has evaluated the effect of trail design and grooming of the slopes on the injury rate and the severity of injury. This study was performed at two Norwegian ski resorts during a five-year period (Bergstrom & Ekeland, 2004). The injury rate and severity of injury decreased significantly after safety measures had been introduced, such as better grooming, repairing of roughness, widening the slopes and opening of new slopes for beginners.

To generate hypotheses and ideas for injury prevention in competitive skiing, more knowledge of why and how the injuries occur is needed. We need to identify factors that play a part in the occurrence of injuries, such as critical risk factors and injury mechanisms (van Mechelen et al., 1992; Bahr & Krosshaug, 2005; Meeuwisse et al., 2007).

Table 5. Studies available on prevention of injuries in alpine skiing

Authors (publ. year)	**Study design**	**Study population**	**Study period**	**Primary outcome**	**Statistical methods**	**Effect**
Bergstrøm & Ekeland (2004)	Prospective survey/surveillance	Skiers and snowboarders (n=1,410)	1990-1996	Injuries treated by ski patrols with an Injury severity scorer of 1-75 (n=1410)	T-test, Pearson's corr. Multiple linear regression	Injury and grooming hours (R^2=0.99), injury and lift journeys (R^2=0.98)
Ettlinger et al. (1995)	Intervention study (awareness training program)	Ski patrols/ski instructions from 25 ski areas (5 drop out) and controls from 22 ski areas	1991-1994	Serious knee sprain (grade III knee sprain and grade II and III ACL sprain)	Chi-square test Exposure data missing	Awareness training reduced the risk of injury by 62%
Hagel et al. (2005b)	Matched case-control and case crossover study	Skiers/snowboarders (n=1,082), 3295 controls with other injuries	2001-2002	Head, face or neck injuries treated by ski patrols	Multiple logistics regression	Helmet use reduced the risk of head injury by 29% (OR 0.71)
Hagel et al. (2005a)	Case-control	Skiers/snowboarders (n=1,082), 3,295 controls with other injuries	2001-2002	Head and neck injuries → ambulance/hospital, or with restriction of daily activities ≥ seven days	Multiple logistics regression	No effect of helmet use on risk-taking behaviour
Hauser (1989)	Intervention study (professional testing and adjustment of the bindings)	Recreational skiers (n=460) and 690 controls	1984-1986	Definition missing (lower extremity injuries)	Not reported	Correctly adjusted bindings reduced the risk of injury (RR 3.5)
Macnab et al. (2002)	Case-control	Skiers/snowboarders <13 years (n=70), uninjured controls	1998-1999	Head, face or neck injuries evaluated at a medical base clinic	Chi-square test and Mantel-Haenzsel test	Higher risk of head injury for non-helmet users (RR 1.77)
Mueller et al. (2008)	Case-control	Skiers/snowboarders (n=3,701) and 17,674 skiers with other injures	2000-2005	Head, face or neck injuries treated by ski patrols	Multivariate logistic regression	Helmet use reduced the risk of head injury by 15% (OR 0.85).
Sulheim et al. (2006)	Case-control	Skiers/snowboarders (n=3,277), 2,992 uninjured controls	2002	Head injuries treated by ski patrols or first aid room staff	Multiple logistic regression	Helmet use reduced the risk of head injury by 60% (OR 0.40)
Jørgensen et al. (1998)	Intervention study with cross-over design (video session on how to ski safety)	Danish skiers (n=243) and 529 controls	1 week	Any physical disability that bothered the patient > 24 h.	Chi-square test, Fishers 'exact and gamma-test	An instructional ski video reduced the risk of injury by 30%.

Aims of the thesis

The main aim of this thesis was to describe the mechanisms of injury in WC alpine skiing, based on systematic video analyses of real injury situations. The specific aims were:

1. To describe the injury situations for all injury types in WC alpine skiing (Paper I).
2. To describe the events leading to ACL injury situations in WC alpine skiing (Paper II).
3. To describe the mechanisms of ACL injuries in WC alpine skiing (Paper III).
4. To describe the knee and hip joint kinematics of typical ACL injury situations in WC alpine skiing (Paper IV).

Methods

This thesis is based on four papers describing the injury mechanisms in WC alpine skiing, employing systematic video analyses of injuries reported through the FIS ISS. Paper I presents a description of the injury situations for all injury types, while Papers II-IV describe the mechanisms of ACL injuries in more detail i.e. the events leading to the injury situations (Paper II), the specific injury mechanisms (Paper III), and knee and hip joint kinematics at the time of injury (Paper IV). Papers I-III are based on visual video analyses, while the MBIM technique is used for the case reports in Paper IV.

Injury registration

The FIS ISS was established prior to the 2006/07 winter season by the FIS in collaboration with the Oslo Sport Trauma Research Center (OSTRC). The aim is to provide and monitor data on injuries in WC skiing and snowboarding. The FIS ISS is based on injury registration through retrospective interviews with athletes, coaches or medical staff from 10 of the largest WC teams (Flørenes et al., 2009; Flørenes et al., 2011). The interviews are conducted by physicians or physical therapists from the OSTRC at the WC finals at the end of each winter season. All athletes who are present in person are interviewed directly, while their coaches or medical staff is interviewed if the athlete is not present (due to injury or for other reasons). Athletes, coaches and medical staff are asked to recall any acute injury sustained by the athlete and which required medical attention, during the five-month WC season in training or competition. The interview is done using a form outlining a week-by-week calendar of the WC season as an aide-memoire. If an injury is recorded, a specific injury registration form is 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). The injury registration process has been described in detail previously (Flørenes et al., 2009; Flørenes et al., 2011).

Injury inclusion and video recording

Papers I-III. We obtained video recordings of injuries reported through the FIS ISS for three consecutive WC seasons (2006-09). In addition, we included injuries reported by technical delegates (TD) at WC and WSC events during the same period (Flørenes et al., 2011) to obtain as many injuries as possible on video. The process to identify videos of injuries is shown in Figure 9. Only time-loss injuries in WC competition were included in Paper I, while we also included ACL injuries from WC official training and WSC events in Papers II and III

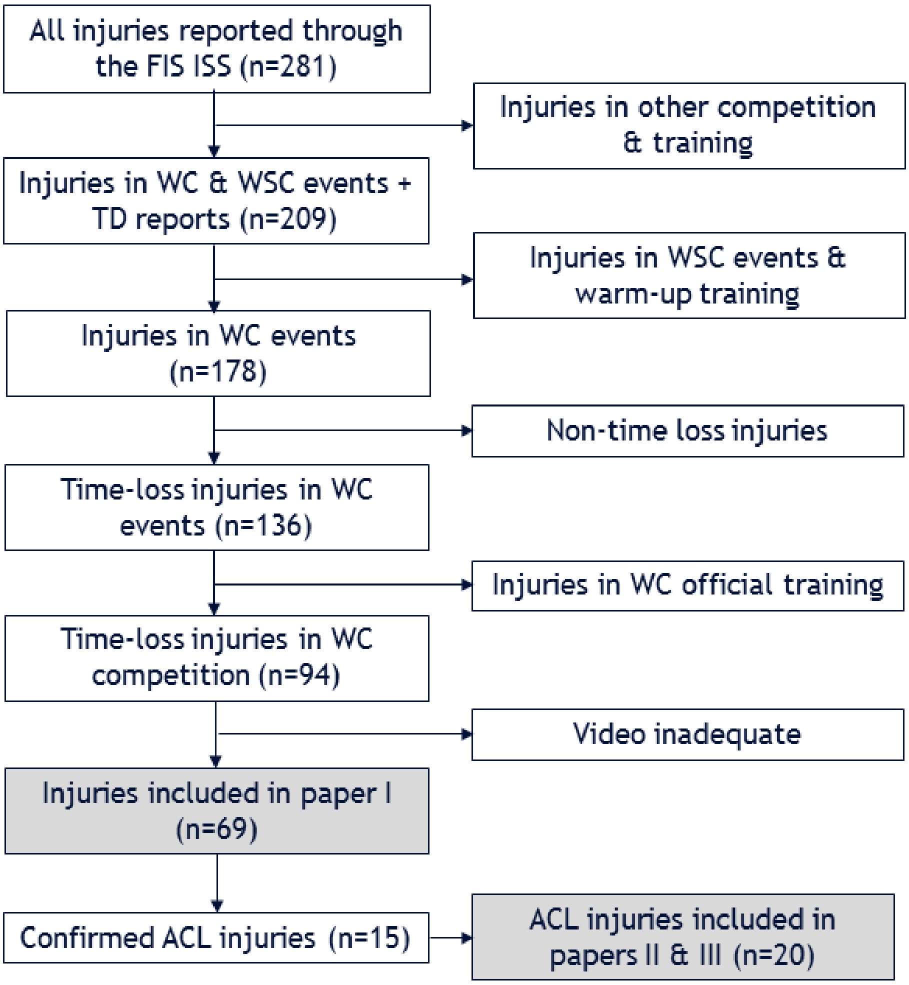

Figure 9. Flow chart showing the process to identify videos of injuries based on injury registration through the FIS ISS (2006-09).

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). Additional footage of confirmed ACL tears from official training (n=3) and WSC (n=2) were obtained directly from FIS or personal contacts within the teams. In this way, we managed to capture all reported and confirmed ACL injuries from WC and WSC events on video.

In total, we had to exclude 25 of the 94 videos from WC competitions, 22 among males and three among females, because the injury situation could not be seen well enough on the video. Of the excluded cases, 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 discipline, the cases occurred in downhill (n=10), slalom (n=6), giant slalom (n=5) and super-G (n=4). However, with respect to 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 time-loss injuries on the WC.

Infront also provided footage of runs by non-injured matched skiers in order to compare injury to no-injury situations in WC 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. The result lists at the FIS website were used for the selection process.

For the ACL injuries, we selected two controls among athletes who completed the run for each of the 15 injury cases from WC competition, as we expected most of the ACL injuries to occur while skiing. For the other injuries, we selected two to four controls among athletes who did not complete the run for each of the injury case, as we expected that the majority of these injuries occur while failing or crashing. However, from the result lists on the FIS website, we did not know why the athlete did not finish the run or to what extent the situations were actually captured on video.

Only 19 of the 30 matched runs obtained for the ACL injures (Papers II and III) and 124 of the 192 matched runs for the other injuries (Paper I) were useful for the analyses. It quickly became apparent that it was not possible to compare the injury situations and matched non-injury situations directly, as they differ considerably with respect to where the athletes skied off course. Nevertheless, the tapes of the matched runs where the skier was not injured were all carefully reviewed and represented useful background information in order to understand the injury situation better.

Paper IV. To describe the joint kinematics of ACL injuries in alpine skiing, utilizing the MBIM technique, at least two camera views where the injured knee is shown clearly from different perspectives are needed for a good result (Krosshaug & Bahr, 2005). One of the ACL injuries reported from the WC seasons 2006-09 was captured from two nearly perpendicular camera views, lending itself to this approach. A 29 years old male alpine skier suffered an ACL tear of the right knee in a slalom WC race in Alta Badia (Italy), December 17th 2007. In addition, an ACL injury reported from the season 2011/12, also classified as a Slip-Catch situation, was captured with four camera views. A 26 years old female alpine skier suffered an ACL tear of her left knee in a parallel slalom WC race in Schladming (Austria), March 16th 2012. Footage of this ACL injury was obtained from the Austrian Broadcasting Corporation ORF (Wien, Austria) and received as a HD video file.

Video processing

Papers I-III. We received video footage from Infront as analogue video files on Beta SP. By using a video editing program (Final Cut Pro, version 6.0.5, Apple, Cupertino, California), we produced 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 video tapes were digitized to QuickTime (.mov) files in 4:3 format (Episode Engine Admin, version 5.0, Apple, Cupertino, California) with a DV 25 PAL codec to preserve the picture quality and to allow for easy frame-by-frame navigation. We used QuickTime Player 7 (Apple, Cupertino, California) to review the videos.

Papers II and III. In addition, we received video footage of ACL injuries from WSC and WC official training as digital files in varying formats (n=5), which were converted to .mov files. For all ACL injury cases included (n=20), 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, USA). In two cases, deinterlacing was not useful.

Paper IV. For the two ACL injury cases, we deinterlaced 640 ms of the video file to tagged image files (TIFF) using Adobe Premiere Pro (version 1.5, Adobe System Inc, San Jose, California) and Adobe Photoshop (version CS, Adobe Systems Inc) to obtain an effective frame rate of 50 Hz. In each case, a manual synchronization between the different camera angles was performed using key events in each camera view (i.e. ski 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 AVI (audio video interleave) file using Adobe After Effects (version CS, Adobe Systems Inc).

Video analysis

Paper I. Five experts in the field of skiing biomechanics, ski coaching and sports medicine related to alpine skiing formed the analysis team. The analysis was organized in two stages. First, the analysts were asked to review the videos individually and complete a form for each injury case (n=69). The form included closed and open questions concerning a) the skiing situation, b) skier behavior and c) piste-related factors (Table 6). 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 an 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 to injury. We did not conduct any training prior to the analysis; the experts were simply asked to analyze 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, as estimated by the first author (TB). If one or more of the analysts disagreed on the time of injury provided, the situation was reevaluated in stage two of the analysis.

Table 6. Variables and categories used in the analysis form to describe each of the injury situations

Variable	Categories
Skiing situation	
Turning	Left, right
Jumping	Take-off, landing
Straight skiing	Gliding, traversing
Unsure	
Skier's behavior	
In balance	Prior to injury, at injury time, after injury
Out of balance	Prior to injury, at injury time, after injury
Falling	Prior to injury, at injury time, after injury Simple fall versus tumbling/sliding
Unsure	Prior to injury, at injury time, after injury
If falling/out of balance	
Influenced by bump on the course	Yes directly, indirectly, no, unsure Prior to injury, at injury time, after injury
If falling	
Direction	Forward, backward, left, right, unsure
Impact contributed to injury	Yes directly, indirectly, no, unsure Initial versus subsequent impact(s)
Impact caused by contact with	Snow surface, gate, safety net, ski, unsure, other
Helmet	
Impact to the head	Yes initial, subsequent, no, unsure Unrelated to injury versus cause of injury
Side of the helmet	Front, rear, left, right, top, unsure
Caused by collision with	Fixed object (describe), snow, unsure
Lost the helmet	Yes, no, unsure Prior to injury, at injury time, after injury
Gate	
Inappropriate gate contact	Yes, no, unsure Prior to injury, at injury time, after injury
Type of contact	Hooking arm/ski, skiing into/through, crash due to previous fall, unsure
Panel release	Yes, no, unsure
Gate release	Yes, no, unsure
Gate break/splinter	Yes, no, unsure
Influenced the skier's control	Yes minor, major, no, unsure
Contact contributed to injury	Yes directly, indirectly, no, unsure
Security net/material	
Contact	Yes, no, unsure Prior to injury, at injury time, after injury
The contact occurred during	Tumbling/sliding after fall, skiing before fall
Type of contact	Caught/stopped into, slightly touched, went over/under, unsure, other
First contact occurred with	The skis, back, head/shoulder, unsure, other
Contact contributed to injury	Yes directly, indirectly, no, unsure

The second stage was a two-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.

Paper II. We invited 14 experts (10 current WC coaches, three former WC coaches and current national team coaches and one recently retired WC ski racer) to review the videos of the ACL injuries (n=20) independently in order to describe in their own words factors they thought may have contributed to each of the injury situations. 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 were described separately (Paper III). The form included open questions to obtain as much expert information as possible and included the following predefined categories: 1) skier technique, 2) skier strategy, 3) equipment, 4) speed & course setting, 5) visibility, snow & piste conditions and 6) any other factors. The experts 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 coaches completed an analysis form for each injury case, and they were provided with information of sex and injured side for each case, as well as the assumed time of injury judged by the analysis team that described the injury mechanisms themselves (Paper III). 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 three to six hours to review the videos carefully and complete the forms.

Paper III. We invited seven international experts in the field of skiing biomechanics and sports medicine related to alpine skiing to form an analysis team, four biomechanists and three orthopaedic surgeons. The analysis process was organized in two parts. The first part consisted of a one-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). Following the individual analysis, the cases were reviewed in a group session to reach a consensus on the index frame. In four cases, there was more than one plausible injury time point, typically during the crash following 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 a) the circumstances of injury, b) the skiing situation, c) skier behavior and d) joint angles and limb positions (Table 7). 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 utilize the deinterlaced sequences and the frame-by-frame function. Additionally, the analysts were provided still pictures of the index frame.

Table 7. Variables and categories used in the analysis form to describe the mechanism of each of the ACL injury cases

Variable	Categories
General	
Visibility	Good, reduced, unsure
Snow conditions	Icy, hard, soft, unsure
Weather conditions	Clear, foggy, snowy, unsure
Type of terrain	Flat, medium, steep, flat to steep, steep to flat/compression, dosed, unsure
Piste conditions	Smooth, rough/bumpy, changes frequently, unsure
Preceding the injury	
Skiing situation	Turning, gliding/straight skiing, traversing, jumping/take off, landing after a jump, unsure
If turning, which phase	Initiation, into fall line, out of fall line, change of turns, unsure
If initial phase, under time pressure	Yes, no, unsure
Speed in relation to course setting	High, normal, unsure
Loss of control	Yes, no, unsure
Turning technique	Carving versus drifting...
Balance	In balance, out of balance (direction)
Weight distribution	Right ski, left ski, both skis
Open question	Please describe the situation preceding the injury in your own words.
At the time of injury (index frame)	
Balance	Still trying to regain balance, given up, already out of, in balance
Knee movements	Flexion/extension, external/internal rotation, valgus/varus, static
Hip movements	Flexion/extension, external/internal rotation, valgus/varus, static
Angles of knee position	Estimated joint angle (°)
Angles of hip position	Estimated joint angle (°)
Position of the arms	Forward, backward, outward, inward, neutral
Angle of attack	Estimated angle (°)
Ground contact ski-snow	Tail, tip, whole length, which edge, unsure
Binding release	Before injury, after injury, no release, unsure
Open question	Please describe the injury mechanism in your own words.
Open question	Please review the control tape(s) carefully and then describe…

Part two of the analysis consisted of a three-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 each of the categorical variables. To obtain a consensus decision, at least four of the seven experts had to agree. If fewer than four experts agreed, the variable was reported as “no consensus”.

Paper IV. We used the MBIM technique (Krosshaug & Bahr, 2005; Krosshaug et al., 2007b) to estimate kinematic characteristics throughout the 640 ms video sequence for each of the ACL injury situations. The matching process was performed using the commercially available program Poser 4 and the Poser Pro Pack (Curious Labs Inc, Santa Cruz, California). A model of the surroundings was built and manually matched to the background video picture for each frame in all camera views. Surrounding landmarks/reference points, such as gate poles and safety nets, were presented in the video sequences, but the exact coordinates of these landmarks were unknown. Thus, we were no able to accurately position the skier in space, but we used the matched landmarks as guidance to determine the camera positions.

We utilized a skeleton computer model from Zygote Media Group Inc (Provo, Utah) for the skier matching. 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 three rotational and three translational degrees of freedom, and the motion of the remaining segments was then described with three rotational degrees of freedom relative to their parent, for example the shank relative to the thigh.

The skeleton model dimensions were based on direct anthropometric measurements of the injured skier. The skis were assumed to be rigidly connected to the feet. Tibia rotation was matched using the ski-boot orientation 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 shrank rotation. The frame-by-frame matching process has been described in detail in previous studies (Krosshaug & Bahr, 2005; Krosshaug et al., 2007b).

A frame of the matched video sequence from one of the cases is shown in Figure 10. To minimize the bias resulting from single-operator judgment, three experts gave their opinion on the matching results. The matching was then adjusted accordingly until a consensus was reached.

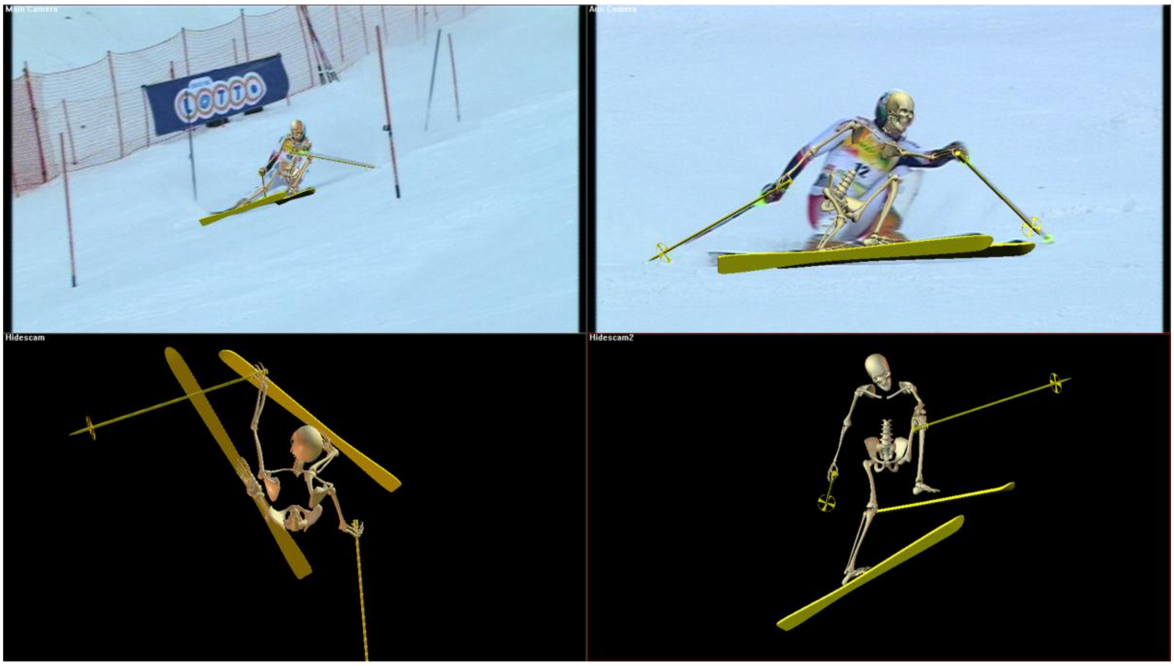

Figure 10. Matching of the injury situation (Case 1), corresponding to 460 ms into the video sequence. The two top images show the customized skeleton model matched to the skier in the background video pictures, while the bottom images show the skeleton model from alternative views generated in Poser.

Data reporting and statistical analysis

Paper I. A chi-square test (95% CI, $p<0.05$) was used to examine whether there was a difference between courses 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.

Paper II. 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.

Paper III. Flexion angles of the knee and hip joints were 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 ms) of the initial, individual estimates from the index frame determined in the consensus meeting (Paper III, Appendix 2).

Paper IV. The joint angle time histories were read into Matlab (MathWorks Inc, Natick, Massachusetts) with a customized script for data processing. Hip and knee kinematics were deduced by the joint coordinate system described by Grood and Suntay (1983).

Ethics

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

Results and discussion

Injury situations in WC alpine skiing

Characteristics of the injury cases (Paper I)

Of the 69 injury 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. More than half of the injuries (n=37) lead to absence from full participation in training and competition >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 the four course sections regarding where the cases (p=0.001) and controls (p=0.043) skied off course. Almost half of the injuries (46%) occurred in the final quarter section. This is supported by previous epidemiological studies, where almost 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 e.g. a higher propensity for skier errors (tiredness, lack of concentration, miscalculation) and challenging race course conditions. However, the injury distribution regarding course section 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.

Time of injury related to falls (Paper I)

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. Interestingly, we found that most of the knee injuries (19 of 23) observed occurred while the skier was still skiing, while the vast majority of head and upper body injuries (27 of 28) occurred while falling (Figure 11). These injuries were caused by contact with the snow surface or objects on the course, such as gates, safety nets/material, or a released ski.

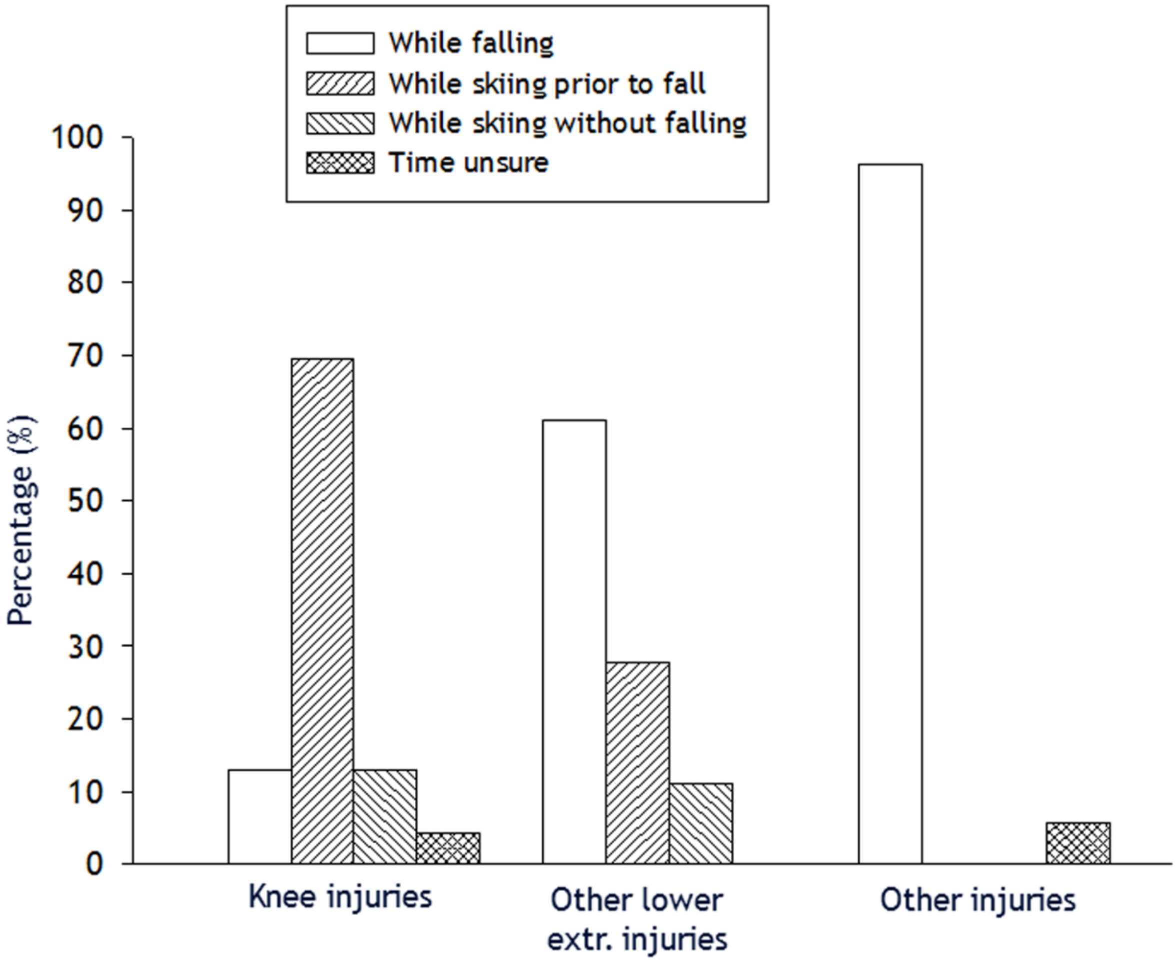

Figure 11. The distribution of injuries regarding the injury time related to falls for knee injuries, other lower extremity injuries and other injuries, expressed as the percentage of the total number of injuries in each category.

Skier contact with gates and safety material (Paper I)

Inappropriate gate contact was perhaps the most notable finding of Paper I, as it contributed to 1/3 (n=21) of all injuries. The proportion was even higher (41%) if knee injuries were excluded. For a skier travelling at speeds of 60 to 80 km/h, which would be typical speeds in GS and SG, hitting a gate of 0.5 kg 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. These injuries 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). Even more common were injuries caused indirectly by gate impacts, upsetting the skier's balance and leading to a fall (n=12). A detailed description of one of these cases is shown in Figure 12.

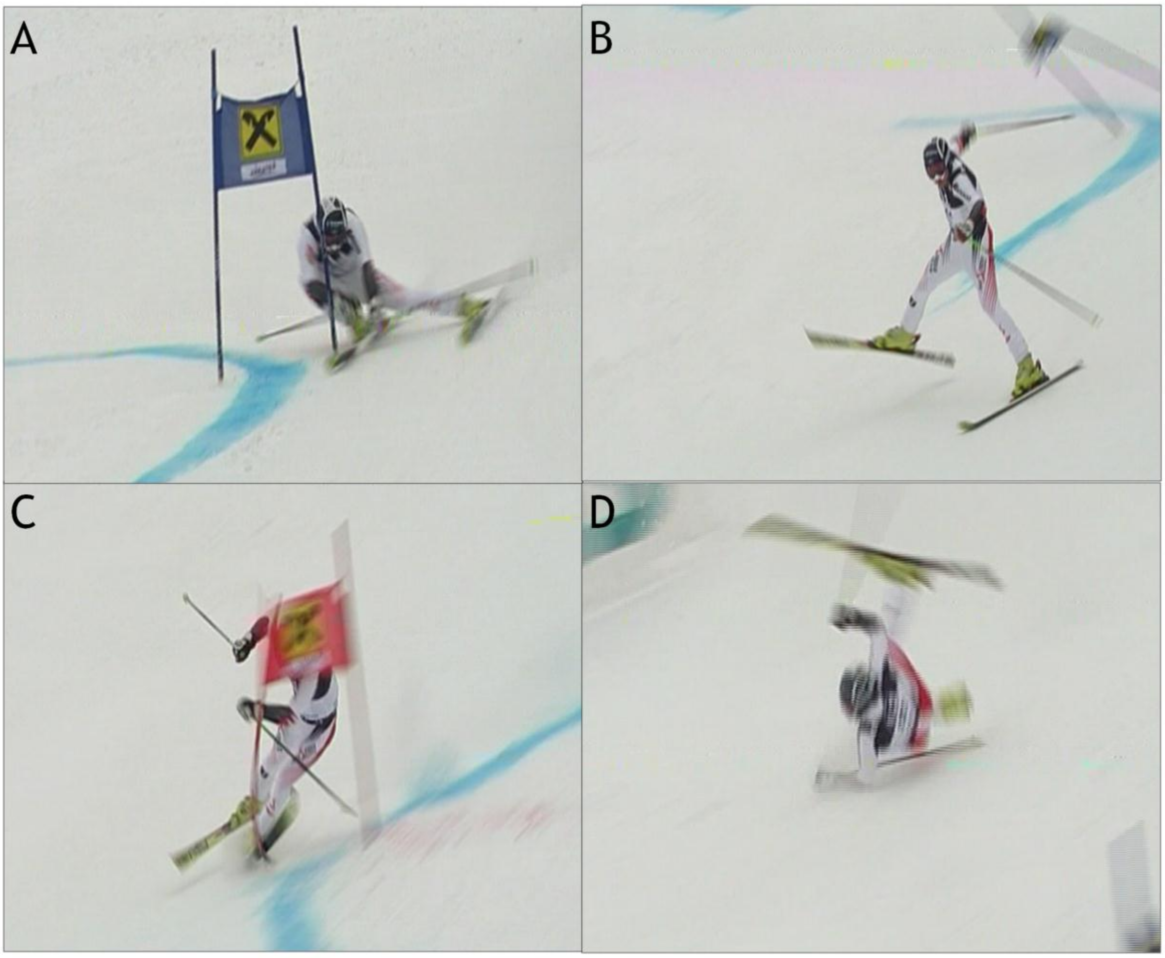

Figure 12. Injury situation leading to a fracture of the upper arm (prox. humerus), left side: ***A*** *(- 1.78 s), the skier has an inappropriate gate contact after a too direct approach into the gate.* ***B*** *(- 1.28 s), he comes out of balance in the turning phase.* ***C*** *(- 0.72 s), the skier hooks the left ski into the next gate, leading to a forward fall.* ***D*** *(assumed time of injury), he lands on his left arm, causing the injury.*

Improvement in pole and panel-release designs may have a potential for reducing the impacts which occur from an inappropriate gate contact. Gate specifications have been changed as recently as in 2008 and 2010 to increase safety (International Ski Federation, 2011c; International Ski Federation, 2011e), but still there may be a potential for further advances in pole construction and panel release systems. 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 could reduce injury risk.

Various safety devices (different safety nets and measures) are used extensively on the slopes to absorb the kinetic energy of a falling skier, as well as to avoid them from crashing into danger areas (e.g. trees, pylons) (International Ski Federation, 2011a; International Ski Federation, 2011f). 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. Although we observed that the skier had contact with safety nets/material in nearly half the cases (n=31), there were only six cases where the injury was judged to occur when the skier was stopped by the net/material. A detailed description of one of these cases is shown in Figure 13. However, judging from the videos, the outcome could have been even worse had the skier not been stopped by the net. 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). 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. Overall, our analyses showed that the safety measures that were in place were efficient in the majority of cases.

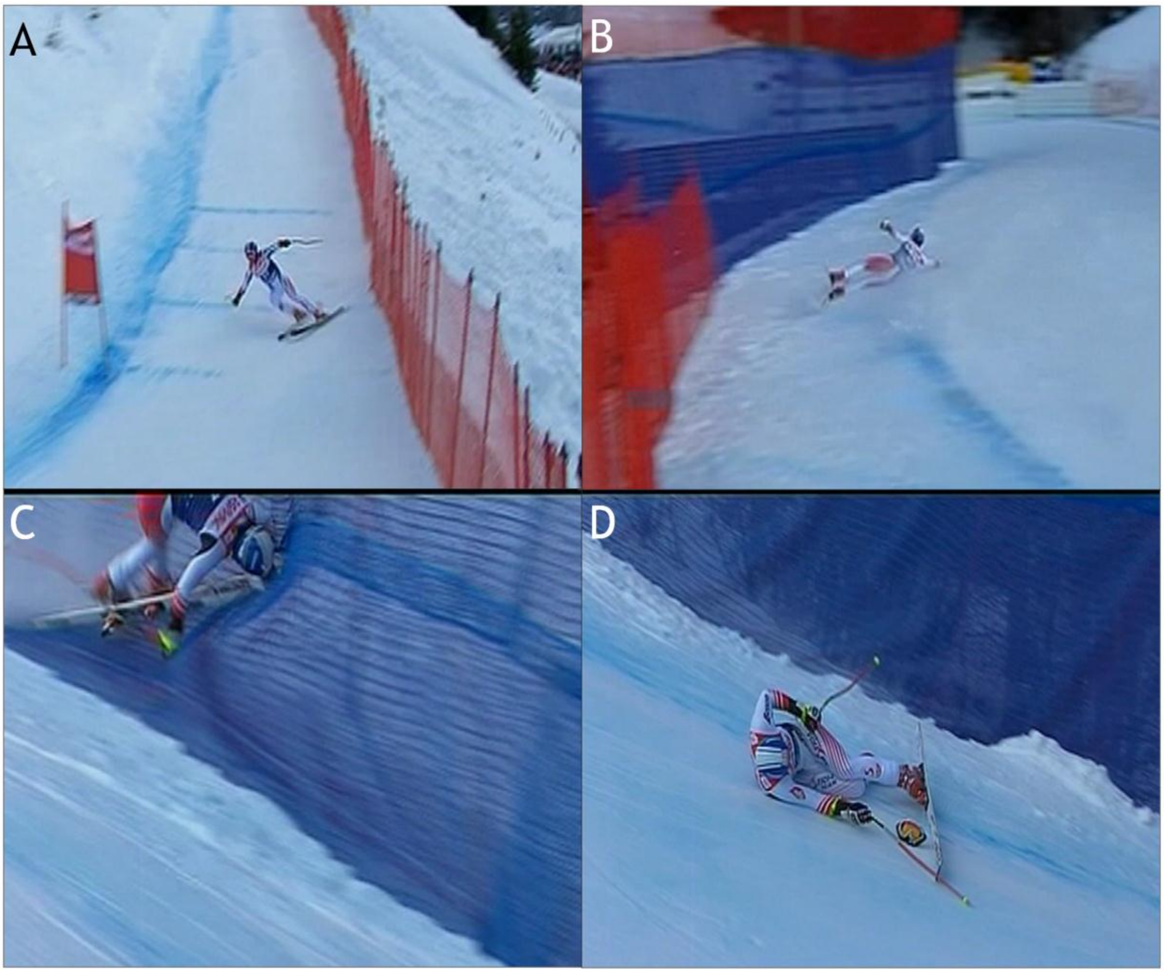

Figure 13. Injury situation leading to a fracture of the tibia and syndesmosis injury, right leg: ***A*** *(- 2.76 s), the skier is out of balance entering a right hand turn.* ***B*** *(- 1.02 s), he falls to his right side and slides into the spill zone.* ***C*** *(index frame), then he tumbles into 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.*

Impacts to the head and upper body (Paper I)

Our analyses show that head impacts occurred in 45 cases, and a concussion or other traumatic brain injury was diagnosed and reported in 12 of these (10 as the main diagnosis and two as an additional injury to a severe lower leg injury). All injuries leading to concussion occurred when the skier hit the head to the snow surface, mainly in the speed disciplines (n=11). A detailed description of one of these cases is shown in Figure 14. The use of a helmet is compulsory for all events, however, current helmet standards for professional racers are similar to those for novice recreational skiers (McIntosh et al., 2011; International Ski Federation, 2011b). As we know that the majority of head injuries among WC athletes occur in the downhill and super-G (Flørenes et al., 2009), it seems reasonable to develop a helmet standard specifically for ski racing, particular for the speed events (McIntosh et al., 2011).

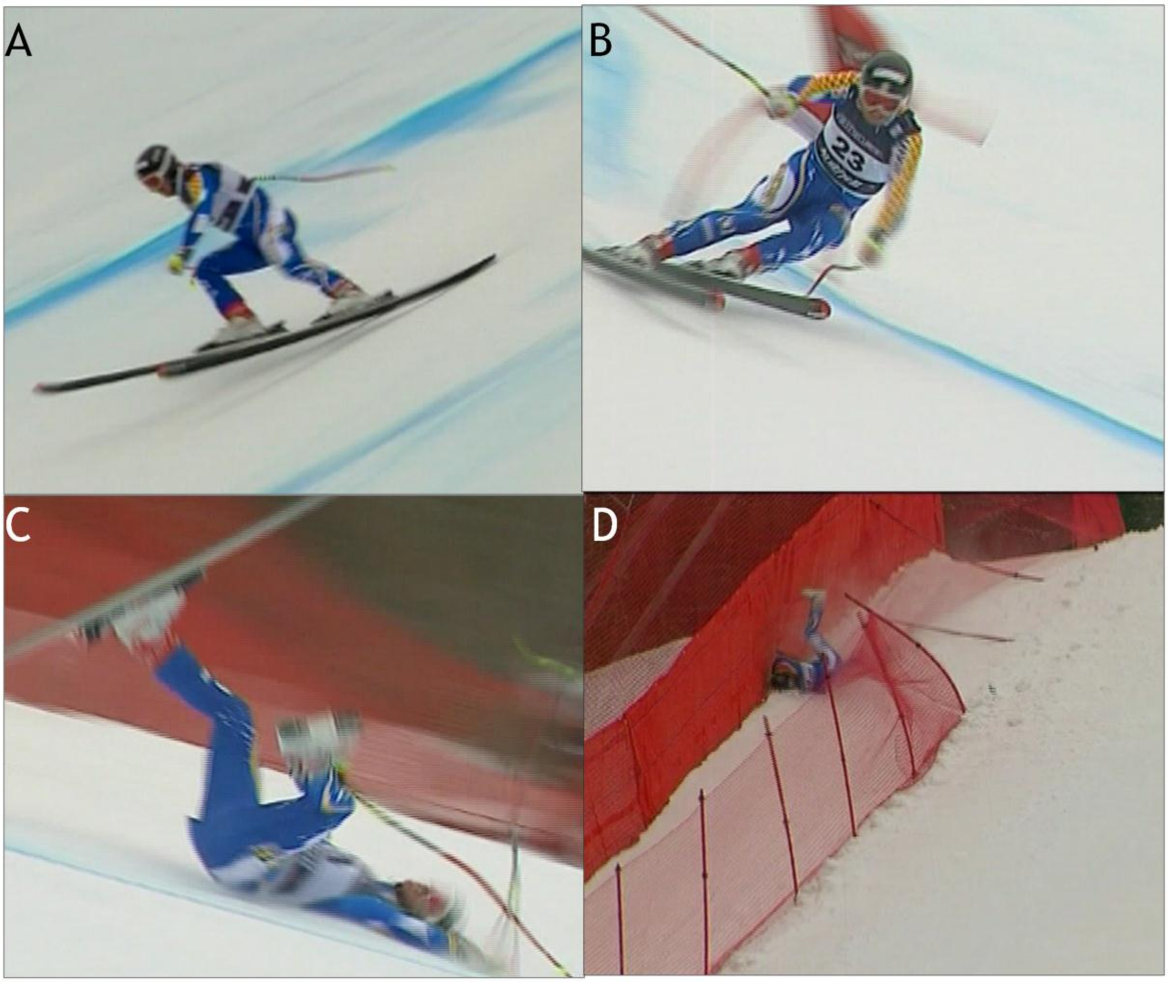

Figure 14. Injury situation leading to concussion: ***A*** *(- 4.24 s), the skier hits some small bumps on the course, leading to an unbalanced position.* ***B*** *(- 2.82 s), an inappropriate gate contact with minor influence on the skier's balance, leading to a left hand fall.* ***C*** *(assumed time 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.*

In total, 17 of the 18 injuries to the upper body were judged to occur as a result of falling (one injury to the back/thorax was not fully covered on the video). 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, most of the protectors must be worn underneath the racing suit (International Ski Federation, 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 (International Ski Federation, 2012b).

We found that the majority of knee injuries (83%) occurred while the skier was still skiing, before or without falling. However, in almost all these cases, the skier was out of balance at the time of injury, unable to control the ski and stabilize the knee. To obtain more specific information about these injury situations, we analyzed the mechanisms for ACL injuries in more detail (Papers II-IV) (Flørenes et al., 2009).

Mechanisms of ACL injury

Based on systematic video analysis of 20 ACL injury cases, the mechanisms were classified into three main categories named the Slip-Catch (n=10), Landing Back-Weighted (n=4) and Dynamic Snowplow (n=3) (Paper III). It is interesting to note that, across the three mechanisms, WC coaches pointed to skier mistakes as the key factors leading to the injury situations (Paper II).

The Slip-Catch mechanism (Papers II-IV)

For the 10 cases classified as Slip-Catch injuries, the skiing situation prior to the injury was consistently characterized by technical and tactical mistakes (Paper II), where the skier came to be out of balance backwards and/or inwards at the time of injury, loosing pressure on the outer ski. In five of the cases, the racer did not manage to absorb terrain changes prior to injury and was too late timing the transition from flat to steep terrain (break-over points) or from steep to flat terrain (compressions). In two other cases, the racer did not absorb changes in the rhythm of the course set, while in the three final Slip-Catch cases, the racer initiated the turn too early. However, we should have in mind that the coaches also reported that in eight of the 10 Slip-Catch cases, bumpy conditions were assumed to contribute to the injury situation. In addition, aggressive snow and icy conditions were each reported to contribute in half of the cases.

At the time of injury, the Slip-Catch cases were characterized by a common pattern where the skier was turning and out of balance backwards and/or inwards (Paper III). The skier lost pressure on the outer ski, which then drifted away from the body's center of mass. The skier extended his 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. A detailed description of one of these cases is shown as an example in Figure 15. This case was also one of the two injury cases analysed with the MBIM technique to estimate kinematic characteristics at the time of injury (Paper IV).

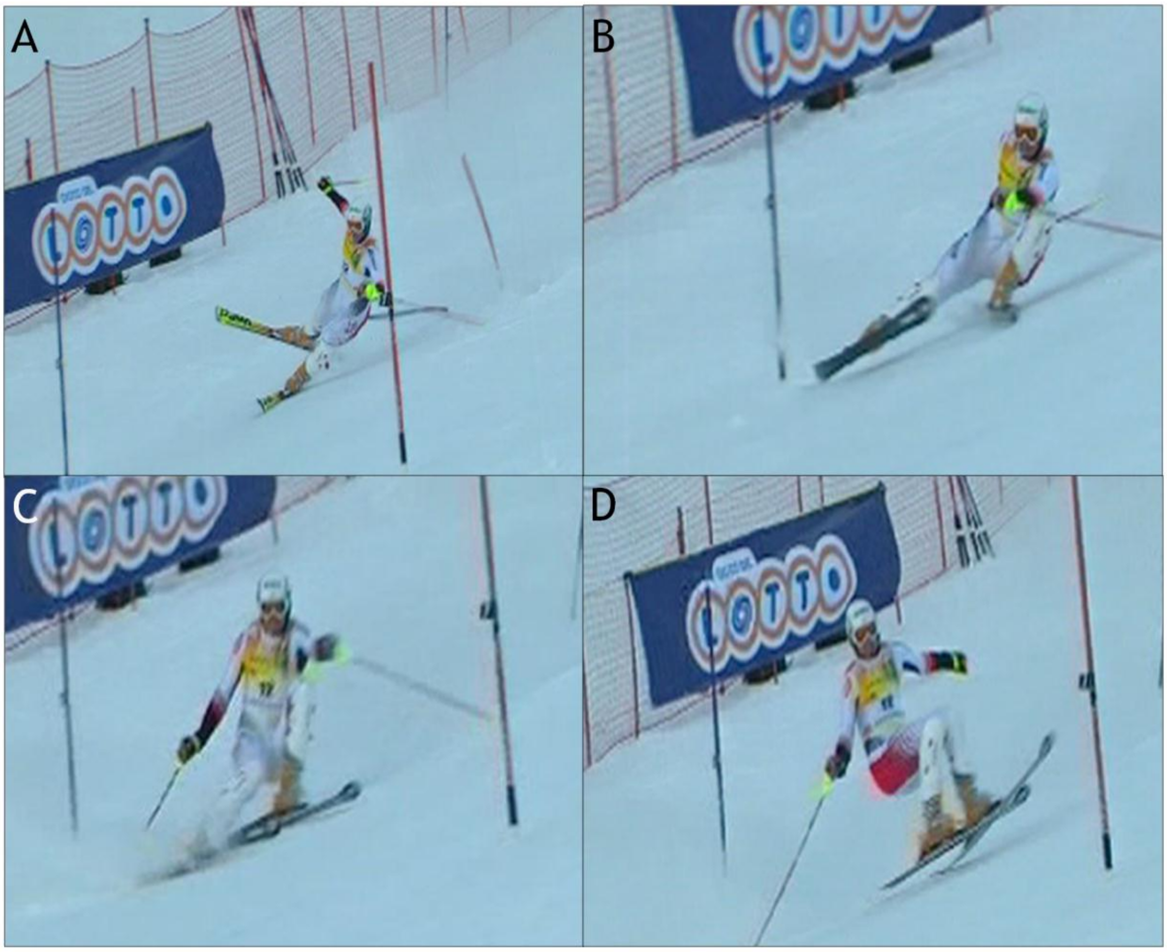

Figure 15. Slip-Catch (right knee). ***A*** *(- 400 ms), the skier is out of balance backwards and inwards in the steering phase out of the fall line.* ***B*** *(- 120 ms), as the skier tries to regain snow contact with the unweighted outer ski, he extends his right knee.* ***C*** *(index frame), the outer ski catches the inside edge abruptly, forcing the right knee into valgus and internal rotation.* ***D*** *(+ 200 ms), the skier falls backwards to his right.*

By using the MBIM technique, we observed sudden changes in knee and hip joint angles when the inside edge of the outer ski caught the snow surface (Paper IV). Within 60 ms, the knee flexion angle increased from 26° to 63° in Case 1 and 39° to 69° in Case 2. In the same period, we observed a rapid increase in tibia 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. Time sequences of the estimated knee and hip joint angles are shown in Figure 16.

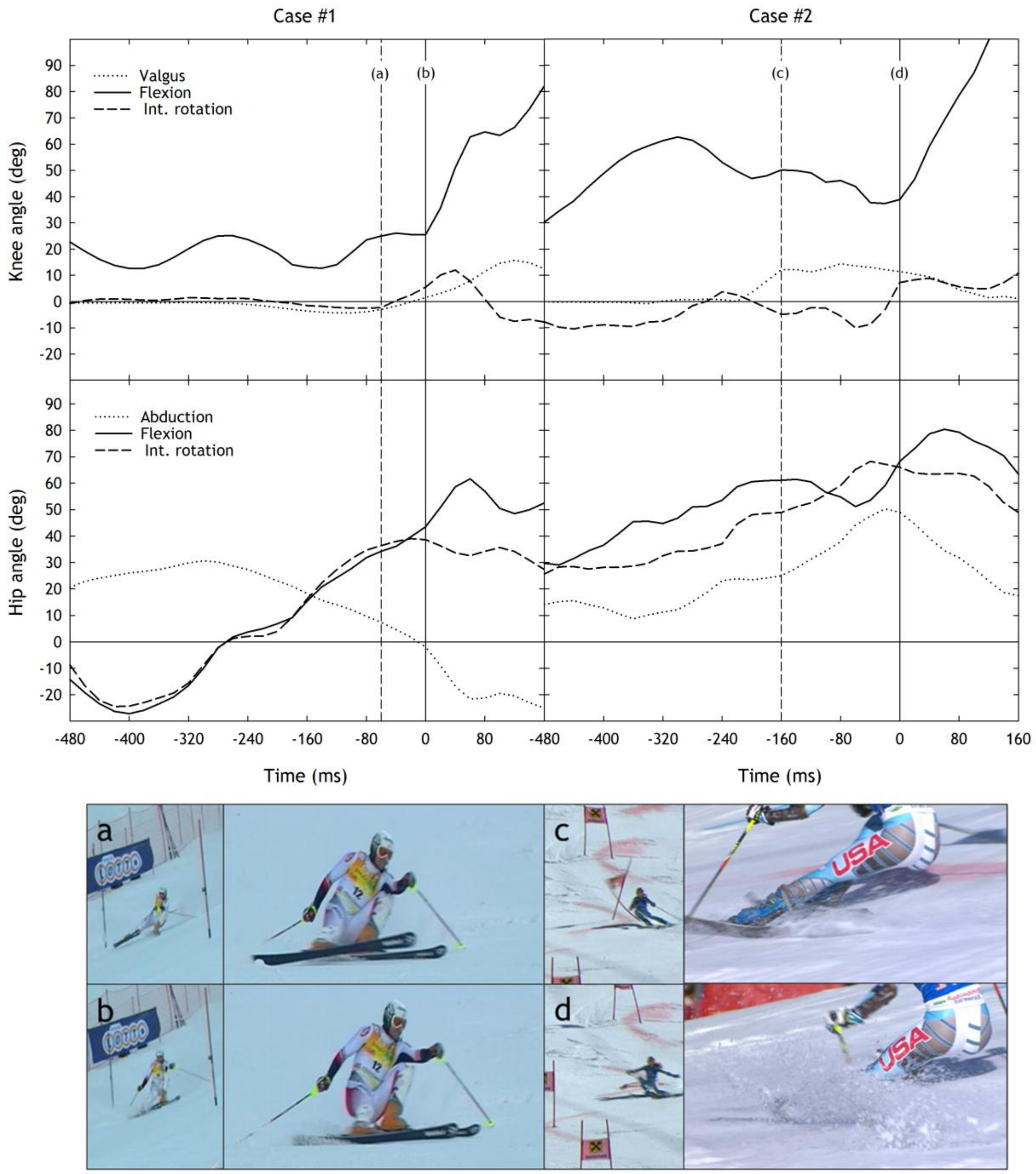

Figure 16. Estimated knee and hip joint angles (deg) of the injured knee (outer leg) throughout the 640 ms matched video sequence. Case 1: The dotted vertical line (a) indicates when the ski tail touched the snow surface, while the solid line (b) indicates 60 ms later, defined as the onset of injury (time 0). Case 2: The dotted vertical line (c) indicates a sudden increase of the knee valgus angle, while the solid line (d) indicates 160 ms later, defined as the onset of injury (time 0).

The Dynamic Snowplow mechanism (Papers II and III)

For the Dynamic Snowplow mechanism (n=3), the racer ended up in a snowplow position with the skis at the time of injury, due to technical and tactical errors prior to injury (Paper II). 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 then not able to react to sudden changes in snow and piste conditions. In one case, the racer hit some small bumps on the course in the turn, and in the two other cases, the racer hit some loose accumulated snow outside the ideal line after the turn, in the traversing section of the course.

In a standing position with inappropriate weight distribution, the unweighted ski drifted away from the body's center of mass (Paper III). The loaded ski then rolled from the outside edge to the inside edge, which subsequently 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 detailed description of one of these cases is shown as an example in Figure 17.

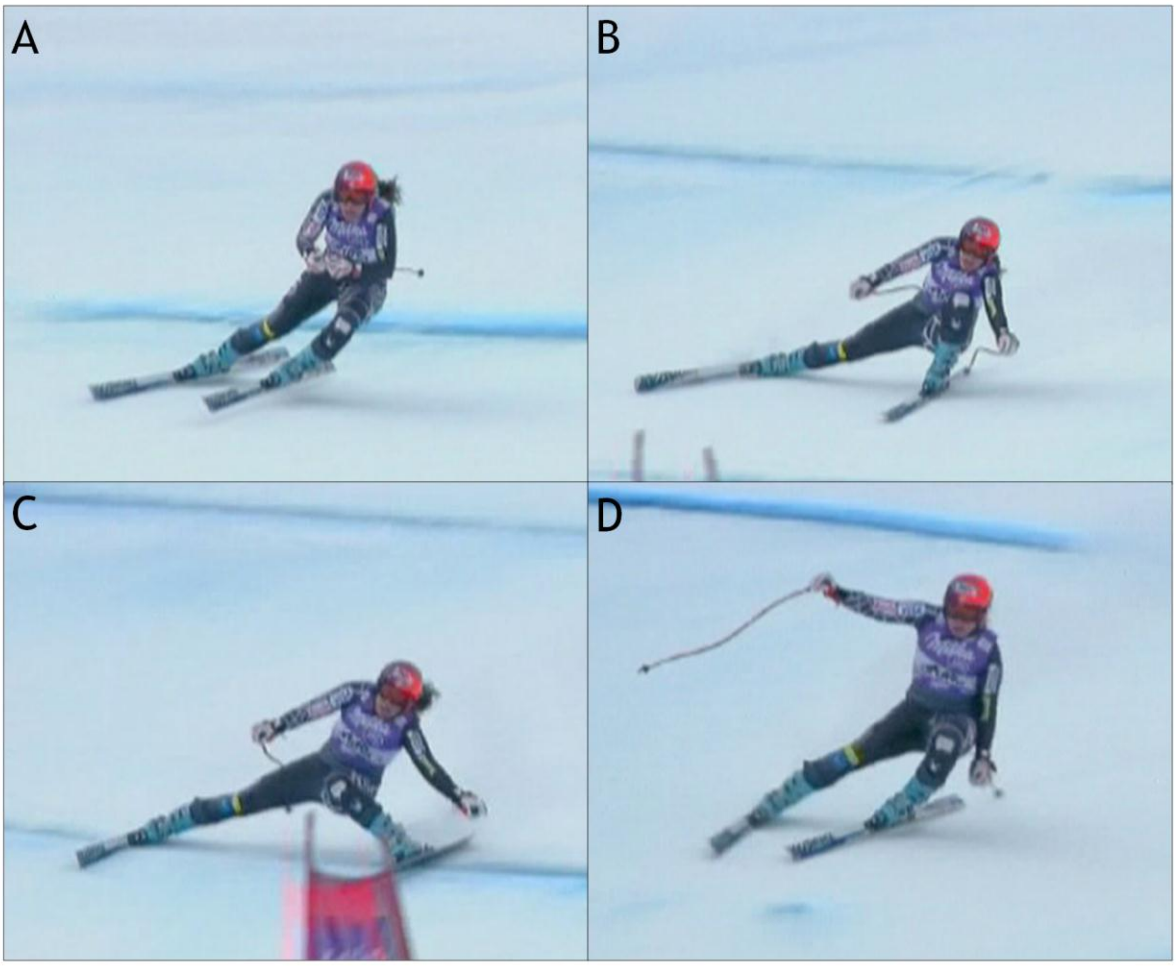

Figure 17. Dynamic Snowplow (left knee). ***A*** *(- 620 ms), due to a small bump, the skier loses ground contact with the inner ski. She gets out of balance backwards and inwards.* ***B*** *(- 240 ms), the right ski drifts away from the body's center of mass, while the inner ski rolls from the outside 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.*

Knee valgus and tibia internal rotation

An interesting feature of the Slip-Catch and Dynamic Snowplow mechanisms is that the end result—internal rotation and valgus loading of the knee—appeared to be very similar in both cases. Previous studies suggest that adverse knee abduction and internal rotation of the tibia relative to the femur may occur when the inside edge of the ski engages the snow surface (St-Onge et al., 2004; Krosshaug et al., 2007b). This motion pattern was described for the "wide snow plow" mechanism by Krosshaug et al. (2007c), based on a three-dimensional motion reconstruction of an ACL injury suffered by a WC downhill racer. In addition, the Phantom Foot, the mechanism claimed to be the most common cause of ACL injures in recreational skiing, also involves internal rotation as one of the main components (Ettlinger et al., 1995). Taking these observations and the results of the current investigation into account, it seems likely that internal rotation and valgus are key components for ACL injury in alpine skiing.

This is supported by findings from biomechanical studies (Markolf et al., 1990; Markolf et al., 1995; Fleming et al., 2001; Hame et al., 2002; Mizuno et al., 2009). The strain generated in the ACL with application of tibial torque at different knee flexion angles was investigated in a cadaveric study (Hame et al., 2002). 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. In addition, a recently developed computer-simulated model for estimation ACL strain in complex 3D loading conditions, reported that the most prominent predictors for ACL strain were anterior shear force, valgus torque and internal rotation torque (Mizuno et al., 2009). The loads also varied as a function of knee flexion angle, with the highest ACL strain occurring between 0 and 20 degree of knee flexion.

By using the MBIM technique in two typical Slip-Catch situations, we found that the leg was abruptly and forcefully compressed from a relatively straight position in both cases (Paper IV). This motion pattern indicates that there is likely a high knee joint compression force involved. Previous studies support that a combination of knee joint compression, tibia internal rotation and knee valgus is an important component of the ACL injury mechanism in team sports like handball, basketball and football (Matsumoto et al., 2001; Hame et al., 2002; Meyer & Haut, 2008; Mizuno et al., 2009; Koga et al., 2010; Oh et al., 2012). A proposed hypothesis is that noncontact ACL injuries seem to occur approximately 40 ms after initial contact and that knee abduction loading and lateral compression generate tibia internal rotation and anterior tibia translation, due to the joint surface geometry and possibly quadriceps drawer, resulting in an ACL tear (Koga et al., 2010). 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 makes a Slip-Catch (and Dynamic Snowplow) situation different from a noncontact ACL injury situation.

In a Slip-Catch situation, we have observed that the skier is out of balance backwards/inwards (Paper III). This will generate an internal tibial torque by two mechanisms. Firstly, a carving ski will rotate inwards, due to the ski's self-steering effect (LeMaster, 2010). In a balanced position, the skier will be able to follow the path of the ski by using appropriate technical approaches (LeMaster, 2010; Reid, 2010), but when the skier is out of balance, he/she may be unable to adjust to the rotatory motion. Thus, the self-steering effect of the ski can generate an internal tibial torque by forcing the ski to carve inwards (Figure 18).

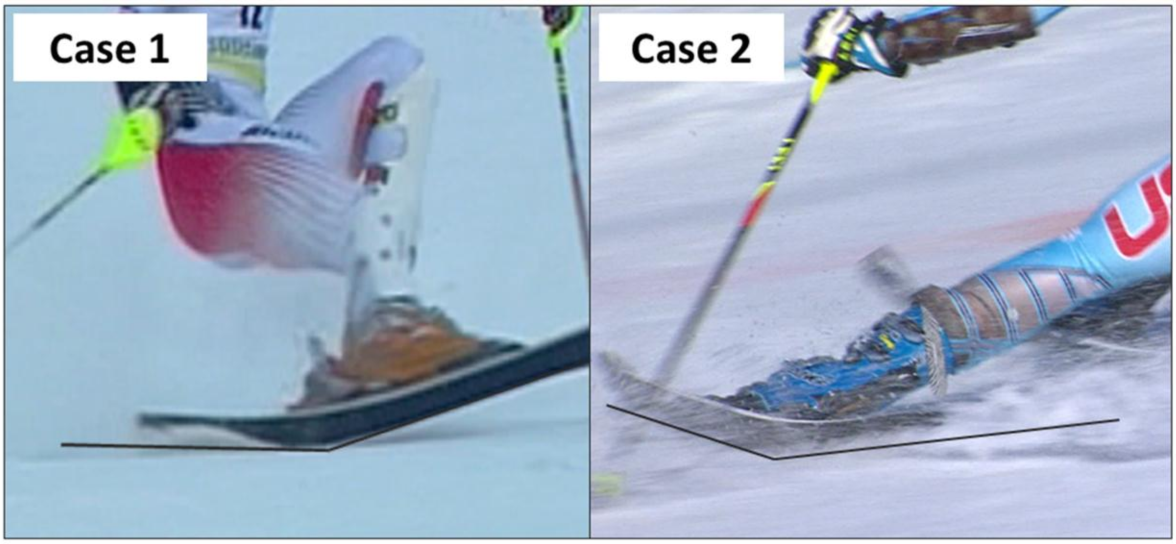

Figure 18. A carving ski will rotate inwards, due to the ski's self-steering effect when a load is applied on the inside edge of the ski. This can generate an internal tibial torque when the load is applied behind the projection of the tibial axis, and the skier is out of balance unable to adjust to the rotatory motion.

Secondly, when a lateral load is applied behind the projection of the tibial axis, the ski will act as a lever to generate internal tibial torque (St-Onge et al., 2004). More backward lean will give a longer moment arm to the tibial axis and thus a larger internal rotation torque (Figure 19a). Although it is difficult to measure reliably 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 is reported that edging a carving ski while turning is associated with knee valgus angles up to 12° (Greenwald et al., 1997; Yoneyama et al., 2000; Bohm & Senner, 2008). An increased knee valgus angle will likely also contribute to increased abduction torque (Figure 19b). Catching an inside edge, while being out of balance backwards/inwards, may therefore represent a serious hazard to the ACL (Krosshaug et al., 2007b).

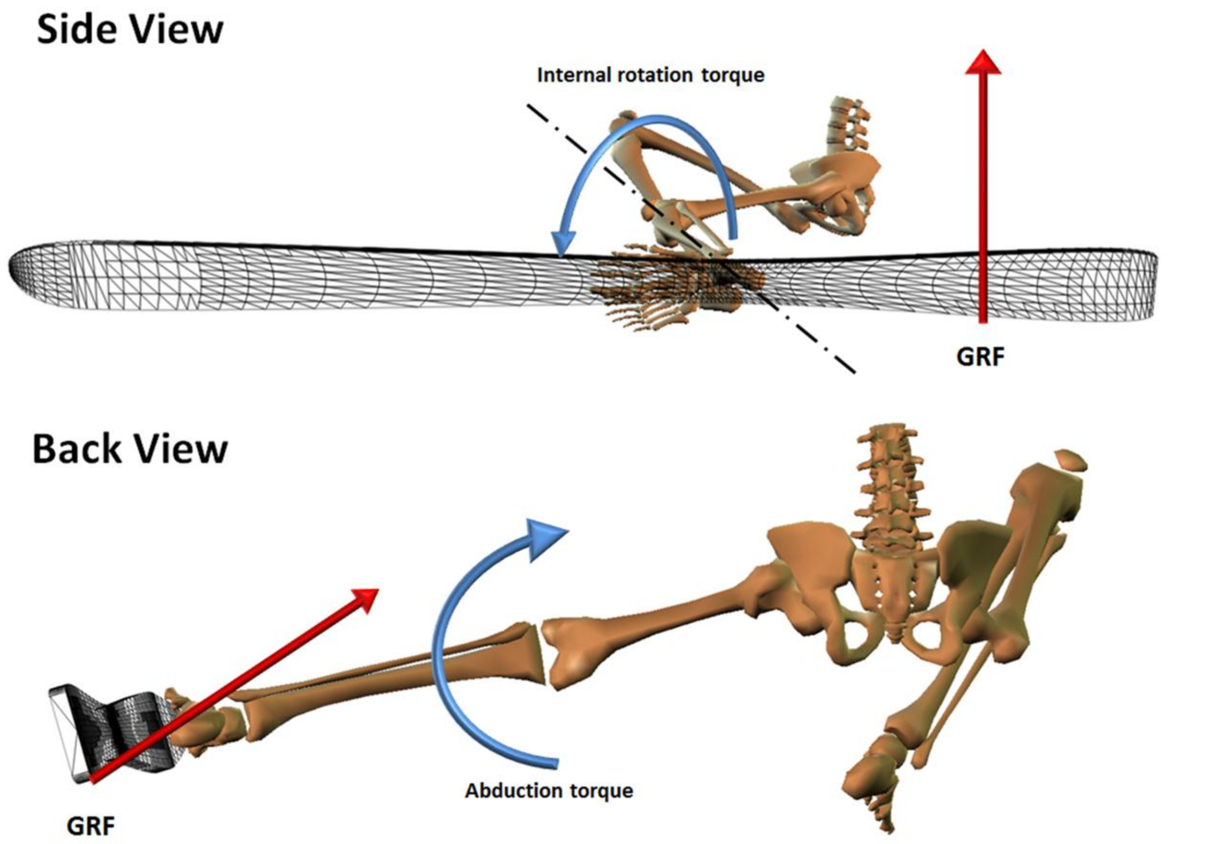

Figure 19. The assumed forces and moments involved in a slip-catch situation. The top image (a) shows a lateral load applied behind the projection of the tibial axis, which acts as a lever to internally rotate the tibia relative to the femur. The bottom image (b) shows how edging a carving ski may cause knee abduction loading.

It is suggested that in a backward bending posture while skiing, a boot-induced anterior drawer (BIAD)(Ettlinger et al., 1995) can also strain the ACL (Koyanagi et al., 2006). In addition, it is suggested that a quadriceps contraction may cause a tibia anterior drawer when the skier tries to recover from an unbalanced position backwards on slightly flexed knees (McConkey, 1986; Geyer & Wirth, 1991). Due to clothing and limited picture resolution, we were not able to evaluate whether a tibia anterior drawer is presented in a Slip-Catch situation (Paper IV). However, based on the sudden changes in joint angles observed with the MBIM technique, we suggest that the ACL injury was caused by a simultaneous knee compression and knee internal rotation and abduction torques. It therefore seems likely that the ACL ruptured shortly after the onset of large changes in knee flexion.

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 estimated injury (Paper III). The same pattern was seen for the other mechanisms. Since the mechanisms of ACL injury have been unknown, it has not been possible to determine the appropriate release criteria for bindings (Ekeland & Nordsletten, 1994; Nordsletten et al., 1996). Based on the data from the current studies (Papers II-IV), it will be a difficult task to design a binding system which can differentiate between adverse internal rotation and valgus loading and aggressive, but normal skiing turns on the other hand.

The Landing Back-Weighted mechanism (Papers II and III)

For the Landing Back-Weighted mechanism (n=4), the skiing situation prior to the injury was characterized by poor jumping technique and incorrect tactical decisions, which resulted in an uncontrolled flight with subsequent landing on the ski tails (Paper II). The skier was in a backward-leaning position at take-off and did not move forward into the hill, due to 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. However, it should be noted that in three of the four cases, the jump was reported to be one of the most challenging on the WC tour.

During the flight phase of the jump, the skier lost balance backwards and, as a result, landed on the ski tails with a large clap angle (Barone et al., 1999) and nearly extended knees (Paper III). As the tail of the ski was loaded, the skis rotated forwards, and the skier attempted to recover his balance. The suggested loading mechanism was a combination of tibiofemoral compression and anterior drawer of the tibia related to the femur. A detailed description of one of these cases is shown in Figure 20.

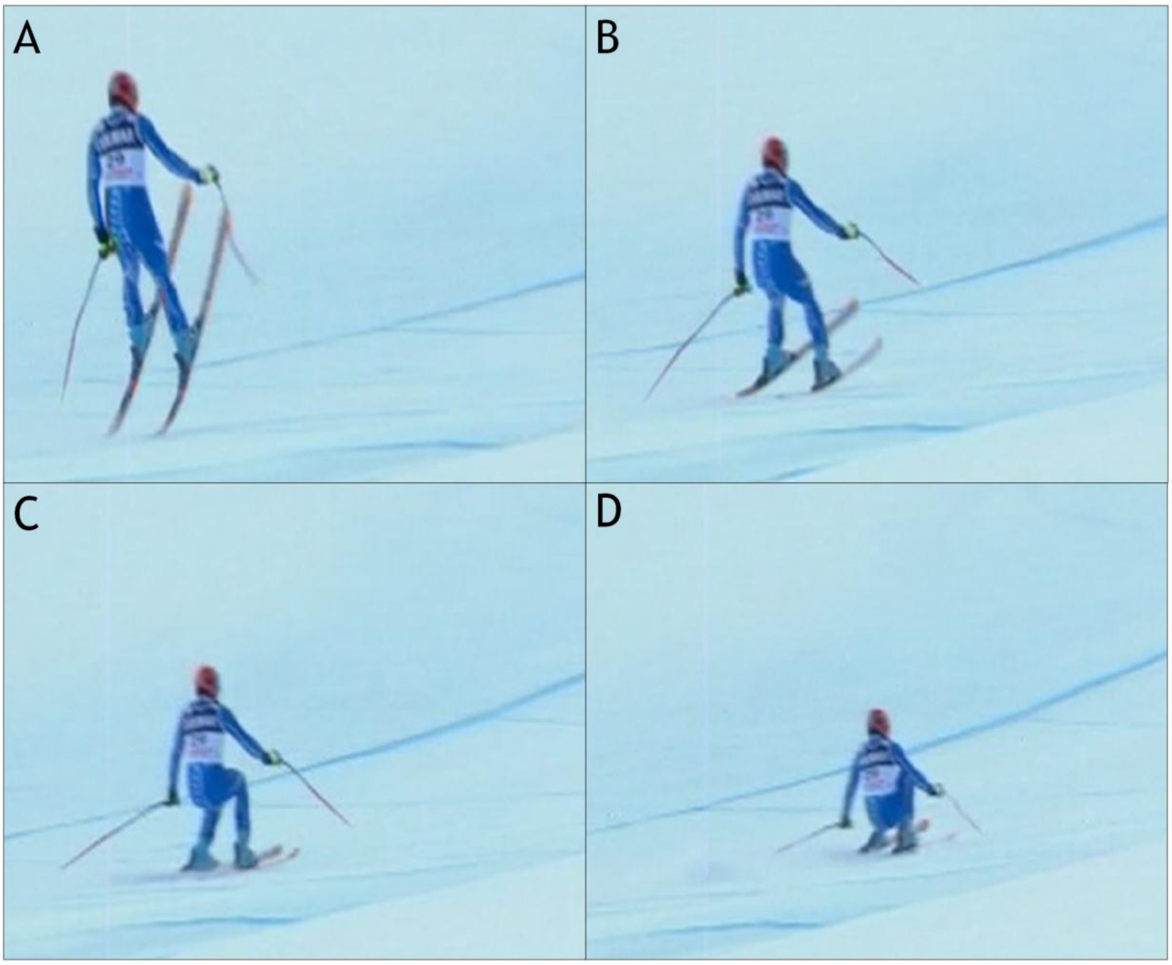

Figure 20. Landing Back-Weighted after jumping (left knee). A (- 420 ms), the skier is out of balance backwards and lands on the ski tails with a large clap angle. ***B*** *(- 160 ms), the right ski hits the snow surface slightly before the left ski.* ***C*** *(index frame), the skier tries to recover from a backward-leaning position.* ***D*** *(+ 240 ms), the skier falls backwards, to the left.*

Tibiofemoral compression and tibia anterior translation

The Landing Back-Weighted situation appeared quite similar to the BIAD mechanism described in recreational skiing (Ettlinger et al., 1995). However, we have elected to refer to this category as Landing Back-Weighted as there may be several loading conditions which can contribute to ACL injury in this situation, not only 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 due to a combination of the BIAD and tibiofemoral compression load (Yeow et al., 2010). Another suggested loading condition that may generate anterior tibial drawer in this situation, is less muscle activation of hamstrings compared to quadriceps. This theory is based on

EMG and kinematics of an accidental ACL injury suffered by a professional racer under experimental conditions (including a reference group) (Barone et al., 1999).

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 (Geyer & Wirth, 1991; Gerritsen et al., 1996; DeMorat et al., 2004), 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 (McConkey, 1986). However, the literature regarding quadriceps contribution to ACL failure is controversial (Gerritsen et al., 1996; Aune et al., 1997; Markolf et al., 2004; Yu & Garrett, 2007). 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 (Ekeland & Thoresen, 1987; Hame et al., 2002).

Another interesting observation we made (Paper III) was that in two of the four 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 (Geyer & Wirth, 1991). However, based on our video analysis, it is not possible to determine which of the theories presented above are more likely, as we cannot be sure of the exact moment of injury while landing after a jump.

Methodological considerations

Visual video analysis (Papers I-III)

For the first time, mechanisms of injuries in WC alpine skiing has been described based on systematic video analyses of real injury situations. Utilizing video recordings, it is possible to describe the injury mechanisms in more detail than retrospective interviews (McConkey, 1986; Fischer et al., 1994; Shimokochi & Shultz, 2008). 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 (Krosshaug et al., 2005). However, there are some limitations to this method of which one should be aware (Krosshaug et al., 2007a; Koga et al., 2010).

Video quality

Visual analysis of video recordings is dependent on the video quality, and this may affect the interpretation of the injury situations. In Paper I, we experienced that it was difficult to judge specific variables in some cases due to the camera position or camera view. 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. More than 70% of the injury situations were captured from only one camera angle. Although several camera angles would help in the interpretation of the videos, we feel confident that, in the majority of these cases, the video quality was sufficient in order to describe the injury situation and the various safety aspects we have addressed. For the ACL injury analyses in Papers II and III, almost 50% of the injury cases were captured from more than one camera angle, and we feel confident that the video quality was not a substantial limitation for the analysts.

It has also been documented that visual 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 (Krosshaug et al., 2007a). In Paper III, our joint angle estimates also varied substantially in some cases, particularly if it was difficult to visualize the hip and knee. To increase measurement accuracy, we strived to obtain the best possible video quality through video processing. Nevertheless, we cannot be sure whether our observations of joint angles and body motion are, in fact, the mechanisms leading to the ACL injury, and not a result of the injury. Thus, the description of joint kinematics reported from visual video analyses should be interpreted with caution. Therefore, we utilized the MBIM technique in Paper IV to describe the knee and hip joint kinematics of two typical ACL injury situations more accurately.

The time of injury

We cannot in all cases be sure of the exact time of injury. Nevertheless, in Paper III, the individual estimates of the index frame were remarkably consistent in most of the ACL injury cases. In some cases, the initial estimates were less consistent with several different initial opinions about when the injury occurred prior to the consensus meeting. In four cases there were more than one plausible injury time point. These were also analysed; however, the alternative injury situations appear less likely than primary time of injury (Paper III, Appendix 2). We have used the first plausible injury situation as the basis for our main conclusions in each case.

The ACL injury time points determined in Paper III were also used for the video analyses of the same cases in Paper I. For the remaining injury cases, the time points were determined by the first author (TB), who had substantial experience in video analysis of skiing injuries. However, 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 have again used the first plausible incident observed as the basis of our conclusion.

Analysis form

When utilizing structured forms to obtain information based on video analyses, a challenge is the use of categories and definitions. This was a challenge in Paper II, where we used one open question for each category in order not to bias the view of the coaches. The assessment of the videos was subjective and qualitative, and there were no consensus meetings during the process. We experienced that some factors were mentioned across the different categories, which made it more difficult to summarize the results. However, this may reflect the fact that injury causation is multifactorial and complex (Bahr & Krosshaug, 2005). 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.

Injury versus no-injury situation

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. Athletes also often ski off course and fall without getting injured. In the same way, bumps, flat light and difficult snow conditions often occur in the WC; yet injury does not necessarily occur. In other words, we do not know how often factors we have described as contributors actually occur during a normal race (Meeuwisse, 2009). The experts reviewed control videos of skiers doing the same run without injury, which formed part of the basis for their interpretation of the injury videos (Papers I- III). However, direct evidence of causation would require a comparison to 'near-injury' situations at the exact same place where the injury occurred, but it is not possible to obtain a systematic sample of such videos. Nevertheless, identifying factors that seem to play a part in the occurrence of injury is an important step to generate hypotheses and ideas for injury prevention (van Mechelen et al., 1992; Bahr & Krosshaug, 2005; Meeuwisse et al., 2007).

The MBIM technique (Paper IV)

To better understand the ACL injury mechanisms, in terms of joint kinematics, we utilized the MBIM technique to provide continuous estimates of knee and hip angles for two Slip-Catch situations, representative of a series of similar injuries from WC alpine skiing (Paper IV). It is difficult to determine the accuracy of the current matching, 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 (Krosshaug & Bahr, 2005; Krosshaug et al., 2007a; Krosshaug et al., 2007b). An advantage of analyzing a skiing injury with this method is that tibia rotation relative to the femur can likely be matched more accurately than for team sports injuries, based on the ski-boot orientation. The tibia rotation was fully assigned to the knee, as the stiff and tight ski boot was assumed to prevent ankle rotation. However, this assumption has not been validated. We also used reference points on the skin-tight racing suit to determine rotation of the thigh and shank. If the suit moves relative to the skin, or more correctly, to the femur, hip rotation, knee rotation and valgus angles may be affected. However, due to the material specifications of the racing suit (International Ski Federation, 2011b), we expect minimal movement of the suit relative to the skin. Three experts gave their opinion on the matching results, and the matching was then adjusted accordingly until a consensus was reached. We performed sensitivity analyses of the matching, where the femur was axial rotated inwards and outwards to ensure that we presented the best possible estimates of knee and hip joint angles.

As described previously, a combination of several approaches is suggested to be the best method to give an accurate and complete description of the injury mechanisms, due to advantages and limitations of the different methodological approaches. In addition to the MBIM technique, detailed information of post-injury clinical findings of the knee could be helpful to better understand the joint kinematics of ACL injuries. Information of associated damages to the meniscus, collateral ligaments, localized cartilage injury and bone bruise could probably support or contradict our observations of the video recordings. The ACL injuries (Papers II-IV) were diagnosed and confirmed as total tears, based on MRI or arthroscopy, prior to the video analyses. However, a copy of the clinical report was available in only some of the injury cases.

Even though video analysis is assumed to be a more accurate approach than retrospective interviews, it might be that some athletes in our studies would be able to provide us with additional information of the injury situations, such as their own opinion of the injury time and injury contributors. However, as this information anyway would be limited, we decided to not disturb the athletes by asking them to recall the injuries in more detail.

Implications for injury prevention

The FIS ISS was established prior to the 2006/07 winter season as part of an initiative by FIS to increase attention on athlete safety and injury prevention. Each athlete has to adapt speed and trajectory to his/her technical skills and individual self-responsible judgement, but rules and regulations regarding racing conditions and skier equipment are set by the FIS to make the sport safe and fair. Knowledge about the injury mechanisms may provide important information about how rules and regulations, as well as skier behaviour, can contribute to reduce the risk of injury and avoid high-risk situations. Our video analyses suggest that ski racer safety may improve by advances in equipment design. We found that the gates contributed to 1/3 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.

Most of the ACL injuries occurred while the athlete was still skiing, without or before falling. This injury situation occurs rapidly due to 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 which will prevent ACL injuries from occurring, risk may be reduced from a combination of measures which can reduce the energy involved in a potential injury situation and give the skier more time to react and adjust. Factors which need to be considered should include the equipment (the ski-plate-binding-boot system), snow conditions (icy and aggressive snow), course setting and speed, and athlete preparation and conditioning.

We found that the injury risk was highest in the final quarter section of the course, and technical mistakes and inappropriate tactical choices were the dominant factors leading to the ACL injuries. An obvious consequence of these observations is to ensure that skier fitness, experience and self-responsible judgment are adequate for WC conditions, especially among the younger and novice WC racers. 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 (Myklebust et al., 2007; Soligard et al., 2008). 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 recognize the risk situations and, if possible, avoid these altogether or respond by 'bailing out' in time. After identifying the Phantom Foot mechanism in recreational alpine skiing, Ettlinger et al. (1995) developed an awareness training program which reduced the ACL 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. Whether similar results could be obtained from such an approach among elite racers is not known.

Conclusions

1. Gate contact contributed directly or indirectly to 30% of all injuries, while the safety nets/material worked as intended in the majority of cases. Almost half of the injuries (46%) occurred in the final quarter section of the course. Most of the injuries to the head and upper body resulted from crashes, while the majority of knee injuries occurred while still skiing.
2. Factors related to skier technique, skier strategy and specific race conditions were assumed to be the main contributors to the ACL injury situations. Skier errors, mainly technical mistakes and inappropriate tactical choices, were the dominant factors.
3. Three distinctive mechanisms of ACL injuries were identified, which we 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.
4. We were able to assess the time course of changes in knee and hip angles for two Slip-Catch situations representative of a series of similar injuries from WC alpine skiing by using the MBIM technique. This study supports the visual video analyses, suggesting that knee compression and knee internal rotation and abduction torques are important components of the injury mechanism in a Slip-Catch situation.

Future research

Although the present studies have provided important information on injury mechanisms in WC alpine skiing, further research is needed.

1. Epidemiological studies should continue to monitor the injury trends over time. WC athletes have also expressed a concern about overuse injuries, and data on these injuries should also be provided and monitored.
2. Video collecting should continue to describe the mechanisms of specific injury types in detail, similar to what we have done for the ACL injuries. This is first of all important for the concussions and severe brain injuries in order to develop new helmet standards. In addition, obtaining clinical findings (MRI, CT, arthroscopy, etc.) of the injuries may increase our understanding of the injury mechanisms.
3. To identify injury risk factors among the athletes, cohort studies should be performed, including pre-season screening of the athletes with prospective registration of injuries and exposure.
4. An intervention study focusing on awareness training of ACL injuries among the athletes could potentially have a preventive effect. An awareness of injury situations and typical skier errors leading to these situations could help the athletes achieve a better understanding of how ACL injuries occur and discuss strategies to avoid them.
5. Even though a relatively precise time sequence of knee and hip joint angles was obtained for two typical Slip-Catch situations, we need to analyze several representative cases utilizing the MBIM technique.
6. Cadaver studies and mathematical simulations, which replicate the injury kinematics obtained from MBIM analyses, could provide useful information of ACL forces/strain in order to determine the exact time of rupture.
7. Finally, more research should be directed towards younger racers, below the WC level. There is a lack of knowledge concerning injury pattern, risk factors, injury mechanisms and preventive measures, yet many are found into premature retirement because of (knee) injuries.

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