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ALPINE SKIING - INJURY PROFILE, ACL INJURY RISK FACTORS, AND PREVENTION

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ALPINE SKIING - Injury profile, ACL injury risk factors, and prevention
THESIS FOR DOCTORAL DEGREE (Ph.D.)

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A contribution and thanks to, Johan, for infused me with your passion for alpine skiing
ABSTRACT

Alpine skiing is a popular winter sport among children and adolescents. The combination of great physical demands and ever-changing external conditions makes competitive alpine skiing one of our most complex sports. To reach the highest level of skiing skill, the skier needs to take part in a long and carefully planned physical training in order to improve skiing performance. This often starts when the skier enters a Swedish ski high school. Like other sports, alpine skiing may unfortunately lead to injuries.

The main aim of the present thesis was to try to reduce ACL injuries in competitive alpine skiers by the use of van Mechelen’s four steps model “Sequence of Prevention”. The first step was to identify the magnitude of the injury problem in terms of injury incidence and injury severity. The second step was to identify risk factors for ACL injuries. The third step was to introduce ACL injury prevention strategies, and finally the fourth step was to evaluate the prevention by repeating the first step.

The cohort of this thesis consisted of alpine ski students, attending ski high schools in Sweden during at least one season between the seasons 2006/2007 and 2012/2013.

In a prospective five year study, injuries in 431 skiers (215 males, 216 females) were recorded. Totally 312 injuries occurred in 193 skiers. The overall injury incidence was 1.7 injuries/1000 skiing hours or 3.11 injuries/100 months as a student at a ski high school. In both male and female skiers most injuries occurred to the knee joint. ACL injuries represented one third of these knee injuries.

ACL injury risk factors were studied. A family history, where either the skier’s father and/or mother had had an ACL injury, increased the risk for this particular skier to sustain an ACL injury. A number of other possible intrinsic and extrinsic risk factors for ACL injuries have also been prospectively studied in 339 skiers (176 males, 163 females). During the study period 25 skiers (11 males, 14 females) sustained a first time ACL injury. There was a higher risk to sustain an ACL injury of the left knee than of the right knee, irrespective of gender. The ACL injured skiers showed a greater side-to-side difference between legs according to functional performance tests. The effect of an ACL injury prevention program was evaluated. The prevention was conducted during a period of 21 months and included those skiers (n=308) that were studying at a ski high school during the seasons 2011/2012 and 2012/2013. Skiers, who attended a ski high school between the seasons 2006/2007 and 2010/2011 were regarded as controls (n=456). The prevention program consisted of a video, and the goal was to teach the skiers how to avoid getting into ACL injury risk situations while skiing. Since there are the same demands on both legs in competitive alpine skiers a number of different neuromuscular exercises as well indoors as outdoors on snow were implemented with the purpose that the skier should carry out equally good performance on both legs. Twelve ACL injuries occurred in the prevention group and 35 ACL injuries occurred in the control group. The incident rate decreased with 0.22 (CI -0.44- 0.00) ACL injuries/ 100 month attending a ski high school in favor of the intervention group.
The conclusion is that the prevention strategies reduced the ACL injuries with 45%. Although, not quite statistically significant, this result could be considered to be of clinical importance on an individual level.
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<td>Anterior Cruciate Ligament</td>
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<td>BIAD</td>
<td>Boot Induced Anterior Drawer</td>
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<td>CI</td>
<td>Confidence Interval</td>
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<td>DH</td>
<td>Down Hill</td>
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<td>FIS</td>
<td>International Ski Federation</td>
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<td>FIS ISS</td>
<td>FIS Injury Surveillance System</td>
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<td>GS</td>
<td>Giant Slalom</td>
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<td>ICC</td>
<td>Intra Correlation Coefficient</td>
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<td>Injury Data Base</td>
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<td>Non-Significant</td>
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<td>OR</td>
<td>Odds Ratio</td>
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<td>OSICS</td>
<td>Orchard Sports Injury Classification System</td>
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<td>ROM</td>
<td>Range of Motion</td>
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<td>SIAS</td>
<td>Spina Iliaca Anterior Superior</td>
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<td>SD</td>
<td>Standard Deviation</td>
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<td>SG</td>
<td>Super Giant Slalom</td>
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<td>SL</td>
<td>Slalom</td>
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<tr>
<td>SLAO</td>
<td>Swedish Ski Lift Organization</td>
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<td>STROBE</td>
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1 SVENSK SAMMANFATTNING

Alpin skidåkning är en av våra populäraste vinteridrotter bland barn och ungdomar.

Kombinationen av höga fysiska krav och ständig beroende av jorden gör alpin tävlingsskidåkning till en av våra mest komplexa idrotter. För att nå den högsta nivån inom alpin idrott krävs en långsiktig och målinriktad träningsplanering. Majoriteten av skidåkarna bygger sin professionella grund på något av våra alpina skidgymnasier. Liksom andra sporter, kan alpin skidåkning tyvärr leda till skador.

Det övergripande syftet med denna avhandling var att försöka reducera antalet främre korsbandsskador inom alpin skidsport med hjälp av van Mechelen’s fyra steg modell "Sequence of Prevention". Det första steget innebar att kartlägga omfattningen av skador avseende incidens och allvarlighetsgrad. Det andra steget innebar att identifiera både individrelaterade och omgivningsrelaterade riskfaktorer för att drabbas av en främre korsbandsskada. Det tredje steget innebar implementering av preventiva åtgärder mot uppkomst av främre korsbandsskada och i det fjärde steget utvärderades preventionen genom att upprepa det första steget.


I en prospektiv femårig studie omfattande 431 åkare (215 män, 216 kvinnor) registreras totalt 312 skador hos 193 åkare. Den totala skadeincidens var 1,7 skador/1000 skidåkningstimmar eller 3,11 skador/100 månaders studier på ett skidgymnasium. Flest antal skador inträffade i knäleden hos båda manliga och kvinnliga skidåkare och främre korsbandsskador representerade en tredjedel av dessa knäskador.

Vidare har riskfaktorer för främre korsbandsskador studerats. En familjehereditet, där skidåkaren antingen har en far och/eller mor med en främre korsbandsskada, ökade risken för denna skidåkare att ådra sig en främre korsbandsskada.

Målet med de preventiva strategierna var att medvetandegöra skidåkarna om en eventuell prestationsskillnad mellan höger och vänster ben samt träna för att prestera mer liksidigt.

Alpin tävlingsskidåkning innebär att skidåkaren bör prestera lika bra svängar till höger som till vänster. Efter att skidåkarna samt deras tränare utbildats i de preventiva strategierna mot främre korsbandsskada uppmanades skidåkarna att regelbundet titta på en video. Videon bestod av en informationsdel samt förslag på olika neuromuskulära övningar att genomföra inomhus och skidövningar att utföra i samband med skidåkning. Tolv främre korsbandsskador inträffade i preventionsgruppen och 35 främre korsbandsskador inträffade i kontrollgruppen. Incidensen av främre korsbandsskador minskade med 0.22 främre korsbandsskador/ 100 månader på ett skidgymnasium i preventionsgruppen.

Konklusionen innebär att de preventiva strategierna reducerade incidensen med 45 % under preventionsperioden. Statistisk signifikans kunde ej påvisas, men resultatet torde sannolikt vara av klinisk betydelse på individnivå.
2 INTRODUCTION

2.1 ALPINE SKIING

In Sweden and worldwide alpine skiing has become one of the most popular sports for children and adolescents. Most individuals, irrespective of age, are skiing for recreational purposes, though. Alpine ski racing has been an Olympic sport since 1936. Today ski racing is organized in four competition disciplines, slalom (SL), giant slalom (GS), super giant slalom (SG) and downhill (DH). There are also two different combination events Combined (C 2 runs of SL and 1 run of DH) or Super Combined (SC 1 run of SL and 1 run of SG or DH). Races are held on natural slopes and each discipline has its own specific course and terrain characteristics. The International Ski Federation (FIS) has regulated the specific competition disciplines by course length, vertical drop from start to finish and course setting.

Slalom is the discipline with the shortest course and quickest turns. Course times are approximately 60-90 seconds per run and the rule of the vertical drop is 140-220 meters.

Giant Slalom consists of a variety of short, medium and long turns. GS has fewer and smoother turns than SL, and the minimum distance between the gates must be 10 meters. The rule of the vertical drop is 250-450 meters.

Super Giant Slalom should consist of a variety of long and medium turns. The course is longer than GS and the minimum distance between the gates must be 25 meters. The rule of the vertical drop is 350-650 meters.

Downhill is the discipline with the smallest number of turns and the longest running time. The shortest run time is 1 minute and the longest 2.5 minutes. The vertical drop varies between 450 and 1100 meters.

SL and GS are suggested to be the most technical disciplines because of the different technical difficulties regarding the courses, and SG and DH are the speed disciplines. In the technical events, each skier makes two runs on the same slope with different course settings. The skier with the shortest combined time of the two runs wins the race. The speed disciplines consist of only one single run down the course and the skier with the shortest time wins the race.

The rules in the combined events are the same as in the individual disciplines. The winner of the combined event is the skier with the shortest total time.

2.1.1 Competitive alpine skiing in Sweden

During the last decade competitive alpine skiing has increased among the younger generation. Today you can start to compete in alpine skiing from the age of 8 years (U8). The competition system is age related and divided into two years age range. From the age of 15 the Swedish Championships are organized for youth athletes in all four disciplines. You become a junior at the age of 17 years and a senior at the age of 22 years. From junior age, the skier needs a license from FIS to participate in national and international competitions and he/she is thereby ranked within the FIS ranking system with FIS points. The FIS points are given in respective disciplines and based on the skier’s race results. Lower points provide better ranking.
In Sweden, about 700 skiers hold a FIS-license and nearly 100% of these alpine skiers, aged 16-20 years, are studying at a Swedish ski high school. The skiers can study either three or four years at a Swedish ski high school. To reach the highest level of competition, the FIS World Cup (WC), the skier needs to take part in a long and carefully planned exercise program, which often starts when they enter a Swedish ski high school. The skiers in Sweden, who have reached the highest level, all have been successful nationally as juniors. Participation in the FIS WC is determined on the national quota of the skier’s national team and the skier’s points.

2.1.2 Profile of demands in competitive alpine skiers

Competitive alpine skiing is one of our most complex sports, based on the combination of great physical demands and ever-changing external conditions. Trying to determine the skier’s level of performance is difficult, since the conditions are never the same. Irrespective of discipline the skier must control the skis throughout the complete curve and force must be applied with necessary kinesthetic sense and timing. To have good control and balance during the different phases of the turn, the skier needs a good performance in several physiological and psychological parameters.

Aerobe/Anaerobe capacity - For alpine skiers, the anaerobic energy processes dominate. Distribution of the energetic systems is 45% aerobic, 55% anaerobic metabolism. Despite the high demand of anaerobic capacity an alpine skier need good values in aerobe capacity. The reason for endurance training is to establish a high enough level to endure the mainly static load of ski racing as well as the overall stress of a long season.

Leg muscle strength - The muscle strength requirements are complex. The external forces arising when sliding down a hill change by turning and edging the skis. This force increase as the speed and the edge angle increases. The highest loads arise during the eccentric phase. The concentric phase is partially relieved and takes place directly after the initiation of the turn. In many sports, the concentric muscle work is lower or the same as the eccentric work. However, in alpine skiing the skier gets energy from the drop height, which is obtained when you go down the hill. This leads to dominantly eccentric muscle actions and explains the relatively high bone strength compared to in other sports. In an EMG study Hintermeister et al. suggested that the primary role of the quadriceps muscle group was to maintain balance while the skier’s carves through the turn.

Core stability - Alpine skiing requires great forces. Therefore, in order to maintain a well-balanced body position while skiing, the skiers need powerful and functional core stability.

Balance and coordination - Alpine skiing is characterized by the difficulties with the ski snow contact. The vibrations, which arise in combination with increasing speeds, place high demands on the skier’s coordination and balance. Therefore it should be included in the training. The purpose of coordination and balance training is to improve motor patterning through neurologic adaptations.

The macro cycle for alpine skiers can be dived into three periods: 1. Preseason (May-July), 2. Sports specific period August-October) and 3. Competition season (November-April).
These macro periods are subdivided in mesoperiods and then further subdivided in micro periods.  

2.2 SPORTS INJURIES - EPIDEMIOLOGY

Swedish Civil Contingency Agency published 2010 a report based on the Swedish Injury Database (IDB) that 280 000 injuries were related to sports and physical activity. This means that almost half of all injuries that lead to a visit at an emergency hospital are related to some form of physical activity and alpine skiing was the third after soccer and ice hockey. To the Swedish Ski Lift Organization (SLAO) 3177 cases were notified during the season 2013/2014 and one fourth of these injuries were located to the knee.

The objective of epidemiological research is to try to prevent injuries. One of the first suggested injury prevention models was described by van Mechelen 1992. According to van Mechelen the Sequence of Prevention consists of four steps. The first step is to try to identify the magnitude of the injury problem by identifying the injury incidence and injury severity specific for the studied sport. The second step means to identify the injury risk factors. In the third step prevention strategies are introduced, and finally in the fourth step the prevention is evaluated by repeating the first step. Finch added another two steps, namely to study barriers and trying to understand motivators before assessing the prevention in a real world context. During the last decade several consensus statements regarding epidemiology injury research for both team sports and individual sports have been suggested. In competitive alpine skiing Flörenäs et al. suggested retrospective interviews with the as well skiers as their coaches in order to get a complete injury surveillance.

2.2.1 Sports injury definition

It is well known that various injury definitions exist in the literature, and therefore it is difficult to compare studies. In 1974 the National Athletic Injury/Illness Reporting Systems (NAIRS) defined a sports injury as an injury which occurs as a result of participation in sports, and limits the athletic participation for at least one day after onset. The consensus statement in football (soccer) defined an injury as “any physical complaint sustained by a player that results from a football match or football training, irrespective of need for medical attention or time loss from football activities”. This definition has led to a somewhat similar definition in other sports. The FIS Injury Surveillance definition means an injury that occurred during training and competition and required attention by medical personnel. A recurrent injury (re-injury) is defined as an injury of the same location and type, which occurs after an athlete’s return to full participation from his/her previous injury.

Injury incidence The incidence of injury is a key variable in the “Sequence of prevention” Rothman defines injury incidence to be the number of subjects developing problems divided with the total time of exposure of a sport. Today the most common way of reporting the injury incidence in sports medicine is the number of injury per 1000 exposure hours.

Injury classification Injury classification refers to the body localization and the damaged structure or tissue. The most common classification system in sports medicine, worldwide is the Orchard Sports Injury Classification System (OSICS). The OSICS system was
developed 1992 by Orchard and has been revised during the years and the latest version is OSICS 10.1. This injury surveillance system is a four character system for coding the body localization (first letter) and the pathology of the injury (letters 2-4).

**Injury severity** The severity level of the injury is related to the injury definition. Van Mechelen described the severity of sports injuries with six closely related criteria. These are the nature of the sport injury, the duration and nature of the treatment, sporting time lost, working time lost, permanent damage and costs. In sports medicine, the severity is usually reported as the time lost from participation in training or competition. The NAIRS system discriminates between minor injuries (1-7 days), moderately serious injuries (8-21 days) and serious injuries (>21 days). Recently, both team sports and individual sports distinguish between minor injuries (1-7 days), moderately serious injuries (8-28 days), severe injuries (>28 days- 6 months) and long-term or career-ending injuries (> 6 months).

### 2.2.2 Sports injury risk factors

The aetiology can be categorised by intrinsic (internal, person-related) and extrinsic (external, environmental-related) risk factors. The intrinsic risk factors are related to the individual biological or psychosocial characteristics of a person such as age, gender, body composition, previous injury, physical fitness and psychosocial stress. Extrinsic risk factors are related to environmental variables such as type of sport, skill level, exposure, match or training, rules, sports facilities (conditions of floor or surface, safety measures, lighting) and equipment (tools, protective equipment, shoes, clothing). The risk factors have also in the literature been categorized as environmental, anatomical, hormonal and neuromuscular.

### 2.2.3 Sports injury prevention

During the last decade the number of studies about injury prevention has increased. The prevention could be categorized into four different areas according to the mechanism of the injuries. 1. Equipment, like protective devices. 2. Training, if the objective was to introduce a neuromuscular adaption. 3. Regulations, if the prevention involved changes in the rules or laws related to the sport/activity. 4 Education if the program was designed to improve knowledge that would lead to a reduced injury risk/rate. A systematic review, the aim of which was to evaluate specific interventions designed to reduce sports injuries showed that most publications focused on protective equipment followed of by training. The most frequently studied sport was soccer and most of the neuromuscular training intervention focused on lower extremity prevention. Moreover, a systematic review, the objective of which was to quantify the effectiveness of prevention programs in children and adolescents, found good evidence that prevention programs could lead to a reduction of injury. Preventions programs have been suggested to be based on the actual sport and its specific injury mechanisms.

### 2.3 ANTERIOR CRUCIATE LIGAMENT INJURY

The anterior cruciate ligament (ACL) is an import ligament in the knee joint whose primary aim is to restrain the tibia translation and secondarily the internal/external rotation and
Most ACL injuries occur in sports including pivoting movements and are characterized as non-contact injuries. Nordenvall et al. reported an incidence rate of ACL injuries in Sweden to be between 78 and 81 injuries per 100,000 individuals and year. Females have six times greater risk for sustaining a non-contact ACL injury than their male counterparts. In Sweden the most common sports-related ACL injury was found in soccer, and the second most common one in alpine skiing when it comes to females and the third most common one in males. The consequences of an ACL injury include both temporary and permanent disability resulting in direct and indirect costs. This serious traumatic injury can lead to major problems for an ACL injured individual in terms of knee joint instability and/or “giving way situations”. Still there is no consensus for the best treatment, physiotherapy alone or reconstruction with subsequent rehabilitation. In Sweden, the rehabilitation period after ACL reconstruction usually lasts 6-8 months.

Recently Smith et al. have published two literature reviews in terms of risk factors associated with an ACL injury. They found decreased intracondylar femoral notch size, decreased depth of the concavity of the medial tibia plateau, increased slope of the tibia plateau, increased anterior-posterior knee laxity to be anatomical risk factors. In addition, a prior reconstruction of the ACL and a family history of ACL injury were reported to be risk factors.

### 2.3.1 Prevention of ACL injuries

A number of prospective studies in terms of prevention of lower extremity injuries have been performed. There are fewer studies where ACL injuries are specified as the outcome measure. An overview of these studies is presented in table 2. All but one out of 16 studies included team sport athletes and mostly soccer players. Only three of these studies included male athletes. After implementation of a prevention program no reduction of the ACL injuries was shown in three of these investigations. The prevention programs differ from each other with regards to type of exercises, length of the program and duration of the intervention period. Caraffa et al. and Söderman et al. used a stepwise balance board training during preseason and indoor season. Other authors but Ettlinger et al. included different exercises, for instance strength training, plyometric training agility training and training for improving balance. Hewett et al. and Heidt et al. conducted a prevention program during to the preseason training, while other authors carried out their prevention programs both during preseason and competitive season. Several authors have recommended to include plyometric, neuromuscular and core stability in the ACL prevention program.

### 2.4 COMPETITIVE ALPINE SKIING - EPIDEMIOLOGY

Some investigations about injury epidemiology in terms of competitive alpine skiers have been carried out. Using a retrospective interview Flørenes et al. performed an injury surveillance of skiers that took part in the FIS World Cup during two winter seasons 2006/2007 and 2007/2008. Bere et al. performed a follow up in FIS World Cup over six seasons. Furthermore, three studies are available, two single event studies, the Olympic.
Games 1994\textsuperscript{24} and the Junior World Championship 1995\textsuperscript{15}. Moreover, a retrospective Finish study using a questionnaire\textsuperscript{119} included competitive alpine skiers has been published. All these studies reported that the knee joint was the most commonly injured body part with a high number of ACL injuries.

2.4.1 ACL injury intrinsic risk factors in competitive alpine skiers

There is limited information about risk factors for sustaining an ACL injury in competitive alpine skiers. The literature is also inconsistent about ACL injury incidence among gender. Stevenson et al.\textsuperscript{120}, Stenroos et al.\textsuperscript{119} and Raschner et al.\textsuperscript{101} reported a higher incidence of ACL injuries in female than male alpine skiers, while other authors did not find any gender difference\textsuperscript{14,31,100}. Only one observational study has evaluated body composition and physical fitness.\textsuperscript{101} In this investigation the authors found core stability to be a critical factor for ACL injuries in young alpine ski racers.

2.4.2 ACL injury extrinsic risk factors in competitive alpine skiers

In solely a few studies ACL injury extrinsic risk factors were evaluated in competitive alpine skiing. From an interview study including 61 experts Spörri et al.\textsuperscript{115} reported 25 “key” injury risk factors to sustain an ACL injury. Ski equipment (boot, binding, plate) was ranked as number one and changes in snow conditions as number two. The experts mean that icy conditions on the slope probably could be safer than aggressive snow conditions, which are consistent with the study by Bere et al.\textsuperscript{13} Furthermore, Bere et al.\textsuperscript{13} reported that technical mistakes and inappropriate tactical choices might lead to injury situations and thereby constituted the highest injury risk. Moreover, Bere et al.\textsuperscript{14} and Flörenäs et al.\textsuperscript{31} found that the downhill race accounted for the highest number of ACL injuries. No correlation between skiing performance/FIS point and injury risk has been found.\textsuperscript{15} Spörri et al.\textsuperscript{115} reported that younger World Cup skiers, in particular female skiers, may not always be adequately prepared for World Cup races.

2.4.3 ACL injury mechanisms in alpine skiing

Slip and catch has been described to be the most common ACL injury mechanism in competitive alpine skiing.\textsuperscript{12} This means that the skier’s outer ski catches the inside edge and forces the knee joint into a combination of internal rotation and valgus (Figure 1). For recreational alpine skiers the Phantom Foot mechanism has been described as the most common ACL injury mechanism (Figure 2).\textsuperscript{27,81} This means that the skier is out of balance, backwards with hips below the knee with the upper body generally facing the downhill ski. The injury occurs when the inside edge of the downhill ski tail recurs the snow surface, forcing the knee joint into a combination of internal rotation and valgus. Other ACL injury mechanisms have been described in the literature. These are the Boot-Induced Anterior Drawer (BIAD),\textsuperscript{27} the valgus external rotation mechanism\textsuperscript{60} and the dynamic snow plow.\textsuperscript{66}
Injury prevention in alpine skiing

In table 1 an overview of ski injury prevention studies is presented. Hitherto, publications of injury prevention in alpine skiers have been focused on recreational skiers. Most of these studies evaluate the effectiveness of using a helmet for injury prevention. One study, Barschera et al. did not find any effect of the use of a helmet. In contrast, five other investigations were in agreement about that the use of a helmet reduces the risk for head injuries. Furthermore, Hagel et al. could not show any relation between behavior risk taking and the use of a helmet while skiing.

Two studies tried to improve the skier’s knowledge about how to avoid injuries and increase skiing safety by watching a video. Ettlinger et al. developed a specific awareness training program, the aim of which was to improve the psychomotor skills and to develop an awareness of possible events leading to an ACL injury during alpine skiing. The program was divided into three parts, avoiding high risk behavior, recognizing potentially dangerous situations and responding quickly and effectively whenever these conditions occurred. They invited ski patrols and ski instructors from 25 ski areas in the USA to participate in this education program. Twenty out of these 25 ski areas completed all training and reporting requirements. The education program included a 19-minute video, a leader’s guide, a flip chart for reviewing information and images covered in the video, a flip chart for recording group responses to questions posed by the video and a workbook for each skier including the video script. Furthermore, 40 skiers were extra trained in the awareness program. After the intervention season a control group was consisted of 22 ski areas. The number of ACL injury from the intervention season was compared with two previous seasons in both groups. The result showed a decreased ACL injury rate in the intervention group with 62% during the intervention season.

Jørgensen et al. performed a randomized intervention study to test the effect of an instructional ski video, which was shown for recreational skiers traveling by bus to the Alps. The skiers (n= 763) were divided into two groups, depending on whether the video had or not had been viewed during the bus transport to the Alps. The video was shown during the outward journey and focused on information about skiing safety including, self-test of release binding, skiing behavior and the ten golden rules for skiers. During the return journey the skiers answered a questionnaire regarding skiing behavior and number of injuries that had happened during the week. The result showed a 30% reduction of injuries in the intervention season.
group compared with the control group and the risk of sustaining a knee injury was lower if the bindings had been tested and adjusted.

To the best of our knowledge only one research group has evaluated prevention strategies regarding skiing environment. This study was performed at two Norwegian ski areas during a five year period. They studied the effect of trail design and grooming hours of the slopes regarding the rate and severity of injuries. Both the injury rate and injury severity decreased after improvement of the slopes (widening slopes, new slopes for beginners, better grooming, repairing roughness.
### Table 1. Studies on injury prevention in alpine skiing.

<table>
<thead>
<tr>
<th>Study</th>
<th>Study design</th>
<th>Study period</th>
<th>Study population</th>
<th>Primary outcome</th>
<th>Statistical methods</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baschera et al. 9 (2015)</td>
<td>Retrospective cohort study 2000-2010</td>
<td>Skiers with traumatic brain injuries (n= 245)</td>
<td>Traumatic brain injuries evaluated with Glasgow coma scale</td>
<td>Multiple regression analysis</td>
<td>Helmet use did not reduce the risk of severe traumatic brain injuries. OR 1.23 (0.52-2.92)</td>
<td></td>
</tr>
<tr>
<td>Bergström &amp; Ekeland. 16 (2004)</td>
<td>Prospective survey 1990-1996</td>
<td>Injured skiers and snowboarders (n=1410)</td>
<td>Injuries evaluated by Injury severity score of 1-75.</td>
<td>Student’s t-test, Pearson’s correlation, Multiple linear regression.</td>
<td>The incident rate decreased after improvement of the slopes. Increased injury rate during the years grooming hours were reduced (r²=0.99).</td>
<td></td>
</tr>
<tr>
<td>Ettlinger et al. 27 (1995)</td>
<td>Intervention study (ACL Awareness Program) 1991-1994</td>
<td>Ski patrols/Ski instructors from different ski areas Intervention group (n=20) Control group (n=22)</td>
<td>Serious knee sprains (Grade III knee sprains and grade II and III ACL sprains)</td>
<td>Chi-square test</td>
<td>The number of serious knee sprains decreased 62% among the trained ski patrols compared with the controls.</td>
<td></td>
</tr>
<tr>
<td>Hagel et al. 42 (2005 a)</td>
<td>Case-control 2001-2002</td>
<td>3295 injured skiers without head face or neck injury. 1. Injury severity 2. High energy crash circumstances</td>
<td>Helmet use</td>
<td>Conditional logistic regression</td>
<td>No differences between non helmet users and helmet users regarding behavior risk.</td>
<td></td>
</tr>
<tr>
<td>Hagel et al. 43 (2005 b)</td>
<td>Matched case-control 2001-2002</td>
<td>Head, neck or face injured skiers (n=1082) 3295 skiers with other injuries</td>
<td>Helmet use</td>
<td>Conditional logistic regression</td>
<td>Helmet use led to 29% reduced risk of head injuries (OR 0.71.)</td>
<td></td>
</tr>
<tr>
<td>Jörgensen et al. 61 (1998)</td>
<td>Intervention study (Injury safety video) 1 week</td>
<td>Skiers traveled by bus to the Alps Intervention group (n=243) Control group (n=520)</td>
<td>A ski injury was defined as a physical disability, that bothered the skiers for &gt; 24 hours</td>
<td>Chi-square test, Fischer’s exact test</td>
<td>A safety instructional ski video significantly reduced the risk of injury in the intervention group.</td>
<td></td>
</tr>
<tr>
<td>Macnab et al. 70 (2008)</td>
<td>Case-control 1998-1999</td>
<td>Skier/snowboarders &gt;13 years (n=70) Uninjured skiers as controls (Estimated by observations)</td>
<td>Helmet use</td>
<td>Chi- square test Matel-Haenzsel test</td>
<td>Higher risk of head injuries for both skiers (RR 1.74) and snowboarders (RR 1.82) that do not use helmet.</td>
<td></td>
</tr>
<tr>
<td>Mueller et al. 76 (2008)</td>
<td>Case-control 2000-2005</td>
<td>Head, neck or face injured skiers/snowboarders (n=3701), 17674 skiers with other injuries</td>
<td>Helmet use</td>
<td>Multiple logistic regression</td>
<td>Helmet use reduced the risk for head injuries (OR 0.85).</td>
<td></td>
</tr>
<tr>
<td>Sulheim et al. 121 (2006)</td>
<td>Case-control 2002</td>
<td>Injured skiers/snowboarders (n=3277), uninjured skiers as controls (n=2992)</td>
<td>Helmet use</td>
<td>Multivarite logistic regression</td>
<td>Helmet use reduced the risk of head injuries (OR 0.40)</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Studies on ACL injury prevention.

<table>
<thead>
<tr>
<th>Study</th>
<th>Study population/sports</th>
<th>Study design</th>
<th>Intervention</th>
<th>Statistical methods</th>
<th>Results: ACL injuries (n) / ACL injury rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caraffa et al. 20 (1996)</td>
<td>Semi- and professional male soccer players Intervention group (n=300) Control group (n=300)</td>
<td>Prospective controlled design during 3 seasons</td>
<td>20 min daily balance board training during the season</td>
<td>Chi-square test</td>
<td>Intervention group: n=10 0.15 injuries/team/season Control group: n=70 1.15 injuries/team/season</td>
</tr>
<tr>
<td>Ettlinger et al. 27 (1995)</td>
<td>Ski patrols/Ski instructors from different ski areas Intervention group (n=20 areas) Control group (n=22 areas)</td>
<td>Prospective controlled design 1991-1994</td>
<td>Education and ACL Awareness Program</td>
<td>Chi-square test</td>
<td>Intervention group: n=16 Control group: n= 29</td>
</tr>
<tr>
<td>Gilchrist et al. 38 (2008)</td>
<td>Female soccer players Intervention group (n=852) Control group (n=583)</td>
<td>Cluster randomized control trial 12 weeks 2002</td>
<td>20 min warm-up program. “ Prevent Injury and Enhance Performance ” (PEP) 3 times per week</td>
<td>z statistic for rate ratio computed using Kish’s formula for the variance of ratio</td>
<td>Intervention group: 7 0.20 injuries/1000 hours Control group: 18 0.34 injuries/1000 hours</td>
</tr>
<tr>
<td>Heidt et al. 47 (2000)</td>
<td>Female soccer players Intervention group (n=42) Control group (n=258)</td>
<td>Prospective randomized design One preseason</td>
<td>Frappier Acceleration Training Program 75 min, 3 times/week</td>
<td>Student’s t-test</td>
<td>Intervention group: 1 Control group: 8</td>
</tr>
<tr>
<td>Hewett et al. 49 (1999)</td>
<td>Female athletes Intervention group (n=366) Control group (n=463)</td>
<td>Prospective intervention study</td>
<td>60-90 min neuromuscular training 3 times per week</td>
<td>Chi-square test</td>
<td>Intervention group: 2 Control group: 5</td>
</tr>
<tr>
<td>Kiani et al. 63 (2010)</td>
<td>Female soccer players Intervention group (n=777) Control group (n=729)</td>
<td>Prospective intervention cohort Season 2007</td>
<td>Harmo Knee program Preseason:2 times/week Season 1 time/week</td>
<td>Fischer exact test</td>
<td>Intervention group: 0 Control group: 5 0.08 injuries/1000 hours</td>
</tr>
<tr>
<td>La Bella et al. 67 (2011)</td>
<td>Female athletes Intervention group (n=737) Control group (n=755)</td>
<td>Prospective randomized study 2006-2007</td>
<td>20 min neuromuscular program before practice</td>
<td>Chi-square test Fischer exact test</td>
<td>Intervention group: 2 0.10 injuries/1000 hours Control group: 6 0.46 injuries/1000 hours</td>
</tr>
<tr>
<td>Mandelbaum et al. 72 (2005)</td>
<td>Female soccer players Intervention group (n=1885) Control group (n=3818)</td>
<td>Cohort study seasons 2000 and 2001</td>
<td>20 min warm-up program, PEP 2 or 3 times per week.</td>
<td>Chi-square test Fischer exact</td>
<td>Intervention group: 6 0.09 injuries/1000 hours Control group: 67 0.49 injuries/1000 hours</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Intervention Details</td>
<td>Statistical Tests</td>
<td>Injury Rates</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>--------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>----------------------------</td>
<td>--------------</td>
<td></td>
</tr>
</tbody>
</table>
| Myklebust et al. (2002)                 | Female handball players | Intervention groups:  
- Season one (n=855)  
- Season two (n=850)  
- Control group (n=942)  
Prospective intervention study 1999-2001  
- 15 min neuromuscular program 3 times a week during a 5- to 7-week training period, and then once/week during the season | Chi-square test  
Fischer exact test  
Wald’s test | Intervention season 1: 23 0.13 injuries/1000 hours  
Intervention season 2: 17 0.09 injuries/1000 hours  
Control group: 29 0.14 injuries/1000 hours |
| Olsen et al. (2005)                     | Handball players | Intervention group (n=958)  
Control group (n=879)  
Prospective randomized study | Cox regression  
Wald test | Intervention group: 3 0.03 injuries/1000 hours  
Control group: 10 0.11 injuries/1000 hours |
| Pasanen et al. (2008)                   | Female floorball players | Intervention group (n=256)  
Control group (n=201)  
Prospective randomized design  
During season 2005-2006 | One way analysis of variance,  
Poisson regression model | Intervention group: 6 0.19 injuries/1000 hours  
Control group: 4 0.16 injuries/1000 hours |
| Petersen et al. (2005)                  | Female handball players | Intervention group (n=134)  
Control group (n=142)  
Prospective case-control study  
One season | Fischer’s exact test | Intervention group: 1 0.04 injuries/1000 hours  
Control group: 5 0.21 injuries/1000 hours |
| Pfeiffer et al. (2006)                  | Female athletes in basketball, volleyball and soccer  
Intervention group (n=577)  
Control group (n=862)  
Prospective cohort study  
Two seasons | Knee Ligament Injury Prevention (KLIP)  
2 times/week | Logistic regression | Intervention group: 3 0.17 injuries/1000 hours  
Control group: 3 0.08 injuries/1000 hours |
| Steffen et al. (2008)                   | Female soccer players | Intervention group (n=1073)  
Control group (n=947)  
Prospective randomized study  
The season 2005, 8 months | One way analysis of variance,  
Chi-square test | Intervention group: 4 0.06 injuries/1000 hours  
Control group: 5 0.08 injuries/1000 hours |
| Söderman et al. (2000)                  | Female soccer players | Intervention group (n=62)  
Control group (n=78)  
Prospective randomized study | Kaplan-Meier survival analysis,  
the log rank test | Intervention group: 4 0.49 injuries/1000 hours  
Control group: 1 0.11 injuries/1000 hours |
| Waldén et al. (2012)                    | Female soccer players | Intervention group (n=2479)  
Control group (n=2085)  
Cluster randomized control trial  
7 months, 2009 | Absolute rate reduction  
Cox Regression | Intervention group: 7 0.05 injuries/1000 hours  
Control group: 14 0.11 injuries/1000 hours |
2.5 RATIONALE OF THE PRESENT THESIS

For competitive alpine skiers an injury is common. Hitherto, all epidemiological studies have reported ACL injuries to be the single most common injury in competitive alpine skiers. In Sweden, nearly all Swedish alpine skiers aged 16-20 years who try to reach the national team attend a ski high school. For the individual skier, an ACL injury has consequences, not only for time lost from skiing but also an increased risk for sustaining a new knee injury and long-term decreased knee function with a reduced activity level as well as an increased risk of early onset of knee osteoarthritis. Not infrequently this injury leads to that the young skier has to end his (or her) skiing career.

The total economic burden of these injuries is not easily quantified, as indirect long-term costs likely overshadow the more readily quantifiable direct costs. From cost effectiveness analysis Swart el al. found that an implementation of neuromuscular programs is more cost effective than screening methods to identify high risk athletes.

However, in order to prevent this serious knee injury the literature recommends that ACL injury prevention programs should be developed for each sport and the intervention must be based on the sport specific ACL mechanism and sport specific intrinsic as well as extrinsic injury risk factors. Moreover, the literature prefers prospective observational studies when planning and implementing a prevention program.

Furthermore, there is a considerable lack of data in terms of competitive alpine skiing in general. Consequently, it is of interest to evaluate whether an ACL injury prevention program specifically developed based on known risk factors and thereby tailored for competitive alpine skiers could lead to a reduction of ACL injuries in alpine skiing.
3 AIM OF THESIS

The main aim of the present thesis was to try to reduce the number of ACL injuries in adolescent competitive alpine skiers by a specifically developed prevention program based on van Mechelen’s “Sequence of Prevention”.¹³⁰

The specific aims were:

Study I: To prospectively follow and study injury incidence, injury location, type of injury as well as injury severity in alpine ski students at the Swedish ski high schools, and additionally to study possible gender differences.

Study II: To investigate a possible relationship between the prevalence of ACL injuries in alpine ski students at the Swedish ski high schools and ACL injuries in their parents.

Study III: To identify potential intrinsic and extrinsic risk factors for ACL injuries in alpine ski students at the Swedish ski high schools.

Study IV: To evaluate whether a specific prevention program could reduce the incidence of ACL injuries in alpine ski students at the Swedish ski high schools.
4 MATERIAL AND METHODS

The present thesis has been based on van Mechelen’s "Sequence of Prevention". Several outcome measures have been used in the four studies included in the thesis (Table 3). A short summary of the study outlines are presented below, followed by a more detailed description in tables and text regarding population, evaluation methods and testing procedure as well as data analysis. Data collection started in August 2006 and was ended in May 2013. The project was preceded by a pilot study during the ski season 2005/2006. The STROBE guidelines for reporting of observational epidemiological studies have been applied in the present thesis.

4.1 STUDY DESIGNS

Study I

An observational longitudinal cohort design was used to identify an injury profile of competitive alpine ski students regarding injury location, type of injury and injury incidence. Four hundred and thirty-one skiers (215 males and 216 females) were prospectively followed at least one season during their study time at a ski high school. The study period started in August 2006 and ended in June 2010.

Study II

A cross–sectional design was used to evaluate a possible relationship between the prevalence of ACL injuries in competitive alpine ski students and their parents. In September 2012 all alpine ski students (n= 593), who have studied at a Swedish ski high school during 2006 and 2012 were invited to answer a questionnaire whether they and/or one or both parents had suffered an ACL injury.

Study III

A prospective cohort design was used to identify possible intrinsic and extrinsic risk factors for ACL injuries in competitive alpine ski students. A cohort of 339 alpine ski students went through a clinical examination and 25 of them sustained a first time ACL injury during the season following the clinical examination. The study was carried out during the seasons 2006/2007 and 2009/2010.

Study IV

A prospective intervention study was used to investigate whether a specific prevention program tailored for alpine ski students at a Swedish ski high school could reduce the number of ACL injuries in this cohort. In September 2011 a specific prevention program was implemented at the ski high schools. The prevention program was focused on each skier’s awareness to perform different exercises equally well on the right as on the left lower extremity. The intervention group consisted of 305 alpine ski students that attended the ski high schools during the seasons 2011/2012 and 2012/2013. The control group (n=431) consisted of those alpine ski students that attended the ski high schools during five seasons (2006/2007 - 2010/2011).
<table>
<thead>
<tr>
<th>Study</th>
<th>Aim of study</th>
<th>Study design</th>
<th>Study period</th>
<th>Participants</th>
<th>Outcome measures</th>
<th>Data analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>To study injury incidence, injury location, type of injury and injury severity in alpine skiers at the Swedish ski high schools and additionally to study possible gender differences.</td>
<td>An observational longitudinal cohort design</td>
<td>2006-2010</td>
<td>n= 431 skiers (215 males, 216 females) that have participated at least one season</td>
<td>Injury location, Type of injury, Injury severity</td>
<td>Descriptive statistics, Injury incidence risk, Absolute risk difference, Kaplan-Meier curve.</td>
</tr>
<tr>
<td>II</td>
<td>To study whether there was any relationship between the prevalence of ACL injuries in competitive alpine ski students and ACL injuries in their parents.</td>
<td>A cross-sectional design</td>
<td>September 2012</td>
<td>n= 418 skiers (187 males, 321 females)</td>
<td>Number of ACL injured mothers and/or fathers of the skiers</td>
<td>Descriptive statistics, Two way logistics regression analysis.</td>
</tr>
<tr>
<td>IV</td>
<td>To evaluate whether a specific prevention program could reduce the incidence of ACL injuries in adolescent competitive alpine skiers.</td>
<td>A prospective intervention study</td>
<td>2006-2013</td>
<td>n= 305 intervention group, 431 control group</td>
<td>ACL injury incidence</td>
<td>Descriptive statistics, Injury incidence risk, Absolute risk difference.</td>
</tr>
</tbody>
</table>
4.2 STUDY POPULATION

The population of this thesis consists of alpine ski students, who have attended a Swedish alpine ski high school at least one season during the study period. During the study period the number of ski high schools especially focused on alpine skiing has changed. The schools are either supported by the Swedish Ski Association or by local ski districts. The participating schools during the study period are presented in table 4. The students are studying during three or four years at a Swedish ski high school. In order to enter the schools the skier must have high previous results in international and national races as merits. The number of skiers included in the thesis is due to the time of data collection for the different studies. In total, 593 alpine skiers have been invited to participate at least one season during the study period (Figure 3).

Table 4. Distribution of the Swedish ski high schools.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Gällivare</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Tärnaby</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Tärnaby</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Sollefteå</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Järpen</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Östersund</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Malung</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Torsby</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Uppsala</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Täby</td>
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</tbody>
</table>

*= The school is supported by the Swedish Ski Association, *= The school is supported by Västerbotten County Council

Study I

Between August 2006 and June 2011 a total of 456 skiers (229 males, 227 females) were invited to participate in the study. Twenty-five skiers were excluded from the study due to that they had not completed their studies at the school (n=19) or due to that they had left the school because of earlier injuries (n=6). Therefore, study I was based on 431 skiers (215 males, 216 females), that were prospectively followed during at least one season.

Study II

In September 2012 all 593 skiers (293 males, 300 females), who have studied at one of the Swedish ski high schools between September 2006 and September 2012 were invited. Two hundred and twelve out of 229 skiers, who still were studying at a ski high school, answered the questionnaire at the yearly personal meeting with the principal test leader (MW). The other 364 skiers were contacted by email and 208 of them completed the questionnaire. Two skiers were excluded because they had no access to the requested information. In total, 418 skiers (187 males, 321 females) answered the questionnaire about personal and family history of ACL injuries, representing a response rate of 70%. The mean age of the included skiers was 20.5±2.6 years.
Study III

Alpine ski students attending a Swedish ski high school between September 2006 and May 2010 were invited to participate in this study. Totally 384 skiers (191 males and 193 females) accepted to participate. Forty-six skiers were excluded from the study, since they did not complete a full year at the school (n=17) or entered the study with a previous ACL injury (n=28, 4 males and 24 females). Consequently, the study was based on 339 skiers (176 males and 163 females) without an earlier ACL injury.

Study IV

In study IV 308 skiers belonged to an intervention group and 456 skiers to a control group. The control group consisted of all available skiers studying at a ski high school between the seasons 2006/2007 and 2010/2011. The intervention group consisted of the skiers attending a school during two seasons, 2011/2012 and 2012/2013. Two ski seasons or 21 months attending a ski high school were the maximal time of exposure for each skier. A total of 28
skiers were excluded from the study, since they did not complete their studies at the school (n=21) or left the school due to earlier injuries (n=7) (Figure 4).

4.3 DATA COLLECTION

The principal test leader visited all ski high schools in August every year and had an individual meeting with each ski student. Before entering the study the skiers received oral and written information about the study and informed consent was collected. The first year the skiers entered the study, they filled out the baseline questionnaire. For those skiers who already were included in the study the individual meeting aimed to check the received data regarding the last season. During the study year, the skiers gave a monthly report by email regarding exposure on snow and possible injury/injuries. In case of injury, the skiers filled out the standardized injury protocol. In addition, the principle test leader regularly contacted the coaches by telephone to ensure that all injuries and time of exposure were reported.

4.3.1 Questionnaires

Baseline (Study I-IV)

The baseline questionnaire (Appendix 1) included demographic date regarding age, number of years in alpine skiing, number of years in competitive alpine skiing, importance of skiing, previous injury or if they had an ongoing injury in terms of injury location.

Time of exposure (Study I)

A time of exposure questionnaire was conducted. The skiers were instructed to fill in the number of skiing hours specified by discipline (Slalom, Giant Slalom, Speed or Free skiing).

Familiar history (Study II)

A questionnaire consisting of personal and family history about ACL injuries was used. Each question was designed to answer "Yes" or "No". If the skier was unsure of his/her family history, he/she was allowed to consult his/her parents.
Injury protocol (Study I, III, IV)

The injury protocol included questions concerning the injury situation (Appendix 2).

Compliance of prevention (Study IV)

A questionnaire with three questions regarding compliance was conducted (Appendix 3).

4.3.2 Clinical examination (Study III)

In connection with the individual meetings between 2006 and 2010 each skier went through a clinical examination. The clinical examinations were performed by one test leader (MW) assisted by two of the authors (MA, SW). All instructions to the skiers were standardized. The skiers were prospectively followed and their first time ACL injury was registered.

Intra-rater reliability tests regarding general joint laxity, knee and foot alignment, anterior knee laxity, varus-valgus stress test, leg length measurement and the muscle flexibility tests were conducted by the test leader (Table 5).

Table 5. Intra-test reliability of clinical tests evaluated within the clinical examination.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Intratester reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>General joint laxity*</td>
<td>1.0</td>
</tr>
<tr>
<td>Knee alignment</td>
<td>1.0</td>
</tr>
<tr>
<td>Foot alignment</td>
<td>1.0</td>
</tr>
<tr>
<td>Anterior knee laxity, KT 1000</td>
<td>0.93</td>
</tr>
<tr>
<td>Varus-valgus knee laxity</td>
<td>1.0</td>
</tr>
<tr>
<td>Leg length measurement</td>
<td>0.98</td>
</tr>
<tr>
<td>Hip flexion with knee extended</td>
<td>0.92</td>
</tr>
<tr>
<td>Hip extended with knee flexion</td>
<td>0.81</td>
</tr>
<tr>
<td>Knee flexion with hip extended</td>
<td>0.86</td>
</tr>
<tr>
<td>Ankle dorsiflexion with knee extended</td>
<td>0.83</td>
</tr>
<tr>
<td>Ankle dorsiflexion with knee flexion</td>
<td>0.73</td>
</tr>
</tbody>
</table>

*General joint laxity was evaluated using a modified Beighton score (Table 6).

General joint laxity was evaluated using a modified of Beighton assessment

Table 6. The modified Beighton scoring system to assess general joint laxity.

<table>
<thead>
<tr>
<th>Score</th>
<th>Assessment of joint mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 point (each side)</td>
<td>Passive hyperextension of the fingers so that they lie parallel to the extensor aspect of the forearm</td>
</tr>
<tr>
<td>1 point (each thumb)</td>
<td>Passive opposition of the thumb to the flexor aspect of the forearm (right or left)</td>
</tr>
<tr>
<td>1 point (each elbow)</td>
<td>Hyperextension of the elbow &gt; 10°</td>
</tr>
<tr>
<td>1 point (each knee)</td>
<td>Hyperextension of the knee &gt; 10°</td>
</tr>
<tr>
<td>1 point</td>
<td>Flexion of the trunk with knees fully extended so that palms rest flat on the floor</td>
</tr>
</tbody>
</table>

≥ 5 points, on a scale from 0-9, was defined as general joint laxity
Anatomical alignment of the knee and foot was determined in a standing position. The relationship between the knee joint and calcaneus was estimated as either varus, normal or valgus.  

Leg length discrepancy was measured with the skier lying on a bench in supine position. The distance from the spina iliaca anterior superior (SIAS) to the medial malleolus of the ankle was measured with a measure tape. A side-to-side discrepancy of $\geq 2$ cm was considered as asymmetry.

Valgus-varus stress test of the knee joint was assessed in 30° of knee flexion. The skier was lying on a bench in supine position. The test leader stressed the knee in valgus and varus and assessed the movement as positive or negative.

Anterior knee laxity was measured with KT-1000 (MED metric Corp., San Diego CA, USA). The test was performed in 30° of knee flexion with the skier in supine position using a foot support to prevent external tibia rotation of both legs. The joint line was marked, the arms were placed along the side of the body and the skier was instructed to stay relaxed from a muscular point of view. Prior to each measurement the KT-1000 was calibrated. The measurements were performed three times on each leg. The highest value of the different measurements (30lb and manual max) was recorded in mm. A side-to-side difference of $\geq 3$ mm was defined as an increased knee laxity (Figure 5).

Ankle dorsiflexion was measured using a goniometer. The measurements were performed with the knee joint in both extension and flexion. The skier was standing with one leg in front of the other leg. With the rear leg in full knee extension and the heel maintained against the floor while loading the flexed front leg, ankle dorsiflexion of the rear leg was measured. With the rear leg in knee flexion and the heel maintained against the floor while loading the flexed front leg, ankle dorsiflexion of the rear leg was measured. One trial of each leg was performed and the result was given in degrees (Figure 6).

Hip flexion with knee extended according to Ekstrand et al. was performed in order to measure muscle length of the hamstring muscles. The skier was measured in supine position with a flexometer (“Myrin”, Follo A/S, Norway) applied to the basis of the patella. The pelvis and the contralateral leg were manually fixed. The skier’s test leg was passively raised with
the knee kept in extension until a maximal hip flexion was reached. The result was given in degrees and one trial of each leg was performed (Figure 7).

*Hip extended with knee flexion* was measured with a flexometer (“Myrin”, Follo A/S, Norway) applied on the basis of the patella. The skier was in supine position with the test leg hanging outside the bench. The contralateral leg was manually fixed in maximal hip and knee flexion. The skier was instructed to keep the test leg relaxed. At this position the degree of hip extension was recorded. The result was given in degrees and one trial of each leg was performed. The test has been suggested to measure flexibility of the hip flexors25 (Figure 8).

*Knee flexion with hip extended* according to Alricsson et al. 3 was performed in order to measure the stiffness of the quadriceps muscle. The skier was measured in prone position lying on a bench with the knee of the contralateral leg slightly flexed and the foot supported on the floor. The pelvis was manually fixed to the bench. Passive maximal knee flexion was performed. The distance between calcaneus and the buttock was measured with a ruler giving the values in centimeters. One trial of each leg was performed (Figure 9).

4.3.3 **Functional performance hop tests (Study III)**

Functional performance hop tests were performed as follows: one-leg hop test for distance, square hop test and side hop test. All hop tests have been described and tested for reliability in healthy athletes and ACL deficient patients.59, 89, 124 The tests were selected to measure different physical demands and to be easy to administer out on the field. The square hop test and the side hop test were video recorded and analyzed by the test leader.

In all three functional performance tests the skiers kept their hands behind the back. The square hop test and the side hop test were tested once and the one-leg hop test for distance was tested three times. The skiers were allowed to perform a few trials of the hop tests prior to the testing.

**One-leg hop test for distance** is suggested to measure explosive muscle strength.124 The skier was standing on the test leg and instructed to hop straight forward, as far as possible, and land on the same leg. The skier was not allowed to move his/her hands from the back. A free leg swing was allowed. The hop was measured from the toe in the starting position to the heel, where the skier landed. The distance was measured in centimeters. The hop was performed three times on each leg (Figure 10). However, if the last trial was the best one, a fourth hop was added.59
Square hop test is suggested to measure a combination of endurance muscle strength, coordination and postural control. The skier was standing on the test leg inside a 40x40 cm square marked with tape (Figure 11). The skier was asked to jump clockwise, in and out of the square during 30 seconds. The number of times that the foot touched inside and outside the square, without touching the tape, was defined as correct jumps. This test was modified from the square hop test by Östenberg.

![Figure 11. Square hop test.](image)

Side hop test is suggested to measure endurance muscle strength modified from the side hop test by Itoh et al. The skier was standing on the test leg and jumped from side to side between two parallel stripes of tape placed 30 cm apart on the floor (Figure 12). The skier was instructed to perform as many correct jumps as possible during 30 seconds. The number of times that the foot touched outside the stripes, without touching the tape, was defined as correct jumps. This test was introduced the second year.

Side-to-side differences of the muscle flexibility tests and the functional performance hop tests were calculated in order to decide whether an asymmetry between the left and right leg was present. The cut-off value was set at 5° in ankle dorsiflexion with extended and flexed knee and in hip extended with knee flexion. The cut-off value for hip flexion with knee extended was set at 10° and in knee flexion with hip extended it was set to 5 cm. In one-leg hop test for distance the cut-off value was set at 10 cm and in the side hop test and square hop test the cut-off value was five jumps.

4.3.4 Intervention - ACL injury prevention strategies (Study IV)

In collaboration with representatives from the Swedish Ski Federation, inspired by the Vermont Skiing Safety Research Group, an educational injury prevention video was developed. The video was based on our injury profile study, identified intrinsic risk factors for ACL injuries in competitive adolescent alpine skiers (to be submitted) and their experience of having a safer/better ski turn to the right or to the left (submitted for publication). The video was produced by two professional film producers.

The video included information about ACL injuries in competitive alpine skiers and education on awareness of how to avoid getting into ACL injury risk situations. In addition, focusing on neuromuscular control and core stability, the video consisted of three indoor functional exercises and three outdoor skiing exercises on snow. The indoor exercises were...
one-leg hop test for distance,\textsuperscript{59} square hop test\textsuperscript{89} and single leg squat.\textsuperscript{57} The outdoor exercises were suggested by the Swedish Ski Federation, the shuffle, the back and forth, and turns with lifted inner ski. The videotape demonstrated how to perform each exercises with proper technique and the skiers were instructed to be aware of whether they were able to perform the exercises equally well on both legs as well as equally well ski turns to the left as to the right.

First year

The prevention program was introduced in September 2011 and all ski coaches were taught how to implement the preventive strategies. The video has been used as a support in order to educate the ski students about ACL injury prevention. They were instructed to watch the movie every third week between September and November (preseason) and once each month between December and April (competition season). The education included information about identified risk factors for ACL injuries in alpine skiing and the importance of stimulating the skiers to perform the suggested exercises. The coaches were informed about the fact that left leg was more often injured and that the exercises should be performed equally good on both legs.

Second year

Prior to the second year the principal test leader educated the new ski students and reminded the other ski students about the prevention strategies by visiting every ski high school at preseason.

During the entire study period the principal test leader had monthly contacts with as well the ski students as their coaches. The reason for these contacts was to ensure data injury collection and information about how the skiers complied with the suggested exercises. Compliance to the training was collected using a questionnaire. At the end of the second year all coaches were re-invited to a meeting in order to secure that all ACL injuries had been recorded and reported to the principal test leader.

4.3.5 Injury definition and classification

Injury definitions

In the present investigation an injury was defined as an injury that occurred during training or competition, which made it impossible for the skier to participate fully in skiing or physical training for at least one training session or competition.\textsuperscript{36}

A previous injury was defined as an injury that the skier had sustained earlier and from which he/she had fully recovered and been allowed to return to skiing before enrolled in the study.

An ongoing injury was defined as an injury from which the skier was still suffering and for whom active rehabilitation was ongoing.

A first time ACL injury was defined as the first time a total ACL injury occurred.
Injury classification

Definitions of injury location and type of injury were based on the Orchard Sports Injury Classification System (OSICS). Injuries to the spine included injuries of the neck, thorax and lumbar spine. Trunk injuries included injuries of the chest and abdomen. All reported ACL injuries in the present thesis were total ACL ruptures, diagnosed by experienced sports orthopedic surgeons.

The classification of the injuries was based on the time-loss definition: minimal injury 1-3 days, mild injury 4-7 days, moderate injury 8-28 days, and severe injury ≥ 28 days.

4.4 STATISTICAL METHODS AND DATA ANALYSIS

The Statistica, StatSoft®, Scandinavia AB, for personal computer was used for statistical analysis in all papers except for study II where the Statistical Package for the Social Sciences, SPSS 20.0 was used. The quantitative data are presented as mean and standard deviation or median and range. Categorical data are presented as frequencies, portions and percentage in all studies. The statistical significant level was set at 0.05. The statistical methods and data analyses used are presented in detail below.

Study I

To compare males and females, the Chi 2 test was used for categorical variables and t-test for continuous variables. Injury incidence rate (IRR) was calculated as the number of injuries per 1000 hours exposure for skiing and as the number of injuries per 100 months attended a ski high school and were presented for males and females with 95% Confidence Interval (CI) for different injury locations. The absolute risk, incidence rate difference (IRD), between males and females for different localization was calculated with 95% CI. P-values for the comparisons were also presented. Poisson distribution and test-based methods were used to construct the confidence intervals. Kaplan-Meier survival curves were calculated for time to the first injury development in groups, skiers with an ongoing injury and skiers without injury at the start of the study and also in groups of skiers that sustained one injury, two injuries, three injuries and four injuries during the study period. In comparisons between the two groups, the non-parametric log-rank test was used.

Study II

An ACL injury in the skier and in one of his/her parents were coded as "Yes" or "No". Furthermore, a variable, "ACL injury of either parent" was encoded in the same way, "Yes" or "No". If either parent or both parents had an ACL injury the code was "Yes". For categorical data the Chi-2 test was used to study possible group differences. The level of significance was set at p <0.05. Two logistic regression analyses with multivariate method were performed to control for gender, where male skiers were coded to 1 and female skiers to 2. In the first step the independent variables were gender and an ACL injured father or an ACL injured mother. The dependent variable was an ACL injury in an alpine skier. The second step was an ACL injured father or an ACL injured mother with the variable "ACL injury of either parent." The results are presented as Odds Ratio (OR) with 95 % (CI).
**Study III**

Differences in continuous variables between the study groups were analyzed using Student’s *t* test. For categorical variables the Chi-2 test was used.

Extrinsic risk factors are presented with cross tables and frequencies and percentages. The exposure data were calculated as the total number of months attending a ski high school and the injury rates (IR) were reported as the total number of ACL injuries per 100 months attending a ski high school. The prevalence of ACL injury was calculated as the number of ACL injuries divided by the total number of skiers. To investigate intrinsic risk factors the values of the latest clinical examination before ACL injury were used, and for the uninjured skiers the values of the latest clinical examination during their participation in the project were used. A Cox proportional Hazard regression model was used to identify intrinsic risk factors for ACL injuries. The time to the first injury was considered important because of the risk that clinical tests may change after injury. Only the first time ACL injuries were included in the analysis. Univariate analyses were performed, entering each variable separately into the Cox regression model. Variables with a p-value < 0.05 in the Cox model were illustrated with Kaplan-Meier curves. The results were reported as Hazard ratios (HR) with 95% (CI). The intra-reliability coefficients were calculated using the method by Bland and Altman.  

**Study IV**

ACL injury prevalence was calculated as the number of ACL injuries divided by the total number of skiers. Time of exposure was calculated as the total number of months that a skier was attending a ski high school and the ACL injury incidence (IR) was reported as the total number of ACL injuries per 100 months that a skier was attending a ski high school. A 95% confidence interval was estimated. The absolute rate reduction of the intervention was calculated as absolute incidence rate differences [IRD= IR (intervention group) - IR (control group)] with 95% (CI). The time to the occurrence of an ACL injury between the groups was calculated and presented with the Kaplan-Meier survival curve.

### 4.4.1 Power analysis

Prior to the study a power analysis was made based on the number of ACL injuries. The power analysis was estimated to detect 25 ACL injuries during an observation period of five years, significance level was set to 0.05 and the statistical power was 80%. The study needed 136 skiers in each group in order to detect the estimated effect with an effect size of 0.35.

### 4.5 ETHICAL APPROVAL

All studies in the present thesis were approved by the Regional Ethics Committee in Stockholm, Sweden.

Dnr 2006/833-31/1 (Study I, III, IV and unpublished data)

Dnr: 2012/1280-32 (Study II)
Prior to entering the studies all skiers and their coaches were given both oral and written information about the studies. Participation was voluntary and all skiers and coaches agreed to participate in this thesis.
5 RESULTS

The thesis is based on a project included 593 alpine skiers attending a ski high schools. The baseline ski related factors are presented in table 7.

Table 7. Demographic data of the skiers at the time when they entered the study.

<table>
<thead>
<tr>
<th>Skiers related factors</th>
<th>Male skiers (n=293)</th>
<th>Female skiers (n=300)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>16.5 ±0.9</td>
<td>16.4±0.8</td>
</tr>
<tr>
<td>Skiing experience (year)</td>
<td>10.1±1.93</td>
<td>10.3±1.89</td>
</tr>
<tr>
<td>Competitive experience</td>
<td>7.7±2.16</td>
<td>7.7±2.19</td>
</tr>
<tr>
<td>FIS-point SL</td>
<td>102±62.5</td>
<td>98±80.1</td>
</tr>
<tr>
<td>FIS-point GS</td>
<td>128±126.7</td>
<td>114±104.9</td>
</tr>
<tr>
<td>Previous injury</td>
<td>172 (59%)</td>
<td>193 (64%)</td>
</tr>
<tr>
<td>Ongoing injury</td>
<td>49 (17%)</td>
<td>81 (27%)</td>
</tr>
</tbody>
</table>

Three hundred and sixty-five out of 593 skiers (172 males, 193 females) reported a previous injury when they entered the study. The lower extremity (hip, groin, knee, lower leg, foot, heel, and toe) accounted for 71% of all injuries.

One hundred and thirty out of 593 skiers reported ongoing injuries when they entered the study. Fifty-two skiers (40%) reported injuries to the knee, and 42 skiers (32%) injuries to other locations of the lower extremity.


Injuries and injury incidence

One hundred and ninety-three skiers (91 males, 102 females) sustained a total of 312 injuries during the five year period that the skiers were prospectively followed. Two hundred and sixty-five injuries (85%) occurred during skiing and 47 injuries (15%) occurred during physical training. There was a total incidence rate for males and females of 1.7 injuries/1000 skiing hours (95% CI 1.51–1.88) or 3.11 injuries/100 months of studies at a ski high school (95% CI 2.77–3.46). The incidence rate for males was 1.62 injuries/1000 ski hours (95% CI 1.36–1.88) or 2.97 injuries/100 months of studies at a ski high school (95% CI 2.50–3.45) and for females 1.77 injuries/1000 skiing hours (95% CI 1.50–2.04) or 3.25 injuries/100 months of studies at a ski high school (95% CI 2.75–3.75). The highest number of injuries/1000 skiing hours was found in the knee joint for both male and female skiers (Table 9).

No significant gender differences were found when it comes to the number of reported injuries. The risk of sustaining a new injury increased the sooner the first time injury occurred (p=0.001). No significant difference was found in this aspect between those skiers who had an ongoing injury and those who were not injured when entering the study.

The absolute risk for being injured showed that males have a higher risk than females to sustain injuries to the hand/finger/thumb (p= 0.01) (Table 9).
Injury location and type of injury

The knee joint was the most commonly injured body part (41%) followed by the spine (12%) and the hand/finger/thumb (11%). The lower extremity (hip, groin, knee, lower leg, foot, heel, and toe) accounted for 58% of all injuries, while 20% occurred in the upper extremity (shoulder, arm, elbow, hand, finger, and thumb).

One hundred and ninety out of 431 skiers (83 males, 107 females) have had at least one injury of the lower leg either before or during the study period. Out of these 190 injured skiers, 120 sustained injuries to their left lower extremity as the first time injury and 70 skiers their right lower extremity as the first time injury (p= 0.001). Female skiers showed a significantly smaller number of lower extremity injuries of their left leg compared to their right leg (p= 0.02), while no significant side-to-side differences were found in male skiers.

Male and female skiers showed the same injury profile in terms of type of injury. Ligament injuries (69%) were the most common injuries.

ACL injuries accounted for 40 (31%) out of totally 127 knee injuries.

Injury severity

One hundred and fifty-two injuries (49%) were classified as severe, while 149 injuries (48%) were moderate and 11 injuries (3%) were mild. Knee injuries followed by spine injuries were the most common locations in terms of severe injuries.

The number of injuries/1000 skiing hours showed an injury incidence of 0.83 for severe injuries, 0.81 for moderate injuries and 0.06 for mild injuries. Using the number of injuries /100 months as a student at a ski high school the figures were 1.52 for severe injuries, 1.49 for moderate injuries and 0.03 for mild injuries.

Table. 8 Distribution of ACL injuries (left versus right knee) during the seasons between 2006/2007 and 2012/2013.

<table>
<thead>
<tr>
<th>ACL injury</th>
<th>Male skiers (n=293)</th>
<th>Female skiers (n=300)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL injury when entering the study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left/Right</td>
<td>6/0</td>
<td>18/12</td>
</tr>
<tr>
<td>First time ACL injury (n)</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Left/Right</td>
<td>10/6</td>
<td>12/8</td>
</tr>
<tr>
<td>ACL re-injury (n)</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Left/Right</td>
<td>3/0</td>
<td>8/1</td>
</tr>
<tr>
<td>Contralateral ACL injury</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
Out of 593 skiers 81 skiers (22 male, 49 female) had undergone a total of 91 ACL injury reconstructions, 60 of the left knee and 31 of the right knee (Table 8). Eighty-nine of these 91 ACL injuries occurred during alpine skiing. The prevalence of ACL injuries was 15, 3%.

Female skiers showed a higher risk to sustain an ACL injury than male skiers ($p = 0.001$). In both gender it was a higher risk to sustain an ACL injury in the left knee compared to the right knee.

Eighteen male and 29 female skiers sustained totally 52 ACL injuries during the seasons 2006/2007-2012/2013. There was a prevalence of 8, 8% ACL injuries and an incidence rate of 0.37 ACL injuries/100 months in ski high school students. Before entering the study 6 males and 30 females had been operated on for totally 40 ACL injuries.

### Table 9. Absolute injury incidence with 95% CI for all recorded injuries (n= 312) among males and females related to injury location

<table>
<thead>
<tr>
<th>Location</th>
<th>Injury incidence (injuries/ 1000 skiing hours)</th>
<th>Absolute risk</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Total</td>
</tr>
<tr>
<td>Head</td>
<td>0.12 (0.05- 0.19)</td>
<td>0.15 (0.07- 0.23)</td>
<td>0.14 (0.08- 0.19)</td>
</tr>
<tr>
<td>Spine</td>
<td>0.16 (0.08- 0.24)</td>
<td>0.26 (0.16- 0.37)</td>
<td>0.21 (0.15- 0.28)</td>
</tr>
<tr>
<td>Chest (sternum, ribs, clavicle)</td>
<td>0.02 (-0.01-0.05)</td>
<td>0.03 (-0.00- 0.07)</td>
<td>0.03 (0.00- 0.05)</td>
</tr>
<tr>
<td>Abdomen</td>
<td>0.02 (-0.01-0.03)</td>
<td>0.00 (0.00- 0.00)</td>
<td>0.01 (-0.01- 0.03)</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0.18 (0.10- 0.27)</td>
<td>0.10 (0.03- 0.16)</td>
<td>0.14 (0.09- 0.20)</td>
</tr>
<tr>
<td>Arm/elbow</td>
<td>0.00 (0.00- 0.00)</td>
<td>0.03 (0.00- 0.07)</td>
<td>0.02 (0.00- 0.03)</td>
</tr>
<tr>
<td>Hand, finger/thumb</td>
<td>0.27 (0.16- 0.38)</td>
<td>0.10 (0.03- 0.16)</td>
<td>0.18 (0.12- 0.25)</td>
</tr>
<tr>
<td>Hip, groin</td>
<td>0.01 (-0.01-0.03)</td>
<td>0.04 (0.00- 0.09)</td>
<td>0.03 (0.00- 0.05)</td>
</tr>
<tr>
<td>Knee</td>
<td>0.61 (0.45- 0.76)</td>
<td>0.78 (0.60- 0.96)</td>
<td>0.69 (0.57- 0.81)</td>
</tr>
<tr>
<td>Lower leg</td>
<td>0.12 (0.05- 0.19)</td>
<td>0.19 (0.10- 0.27)</td>
<td>0.15 (0.10- 0.21)</td>
</tr>
<tr>
<td>Foot, heel, toe</td>
<td>0.12 (0.05- 0.19)</td>
<td>0.09 (0.03- 0.15)</td>
<td>0.10 (0.06- 0.15)</td>
</tr>
<tr>
<td>Total</td>
<td>1.62 (1.36- 1.88)</td>
<td>1.77 (1.50- 2.04)</td>
<td>1.70 (1.51- 1.88)</td>
</tr>
</tbody>
</table>

Injury incidence with 95% CI between male and females in shown for each injury location and the absolute risk for males versus female

### 5.2 ACL INJURIES

Out of 593 skiers 81 skiers (22 male, 49 female) had undergone a total of 91 ACL injury reconstructions, 60 of the left knee and 31 of the right knee (Table 8). Eighty-nine of these 91 ACL injuries occurred during alpine skiing. The prevalence of ACL injuries was 15, 3%.
5.2.1 ACL injury - Intrinsic risk factor

Clinical examination

There were no significant differences between skiers, who sustained a first time ACL injury and skiers who did not with respect to age, BMI, skiing experience and previous injuries.

Anthropometric data, muscle flexibility tests and functional performance hop tests are presented in tables 10 and 11, respectively. The ranges and standard deviations were smaller in all measured variables in ACL injured skiers compared to those without an ACL injury when it comes to muscle flexibility tests and functional performance hop tests. A Cox proportional hazard regression model was used to identify intrinsic risk factors for ACL injuries (Table 12).

The ACL injured group showed an increased side-to-side difference in the one leg hop test for distance (Table 10). When judging the skier’s side-to-side performance, equally good/unequally good performance between legs in terms of the functional hop tests, the ACL injured group showed a higher percentage of unequal side-to-side difference than the group without an ACL injury (Table 10).

Table 10. Functional performance hop tests.
Group differences were analysed with Chi-2 test and Student’s t test.

<table>
<thead>
<tr>
<th>Functional performance hop tests</th>
<th>ACL injured skiers (n=25)</th>
<th>Skiers without an ACL injury (n=314)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One-leg hop test for distance (cm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left leg a</td>
<td>158 (119-198)</td>
<td>157 (104-235)</td>
</tr>
<tr>
<td>Right leg a</td>
<td>150 (105-191)</td>
<td>156 (102-227)</td>
</tr>
<tr>
<td>≥ 10 cm side-to-side diff. b</td>
<td>9 (36%)</td>
<td>72 (23%)</td>
</tr>
<tr>
<td><strong>Square hop test</strong> (number of correct hops)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left leg a</td>
<td>76 (63-90)</td>
<td>74 (52-108)</td>
</tr>
<tr>
<td>Right leg a</td>
<td>76 (56-86)</td>
<td>75 (50-104)</td>
</tr>
<tr>
<td>&gt; 5 side-to-side diff. b</td>
<td>15 (60%)</td>
<td>136 (43%)</td>
</tr>
<tr>
<td><strong>Side hop test</strong> (number of correct hops) *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left leg a</td>
<td>66 (49-73)</td>
<td>61 (31-81)</td>
</tr>
<tr>
<td>Right leg a</td>
<td>63 (51-74)</td>
<td>62 (33-82)</td>
</tr>
<tr>
<td>&gt; 5 side-to-side diff. b</td>
<td>10 (63%)</td>
<td>132 (50%)</td>
</tr>
</tbody>
</table>

a Median and range  
b Number and percentage  
* ACL injured skiers (n=16), skiers without an ACL injury (n=265)
Table 11. Anthropometric data. Group differences were analysis with Chi 2- test and the Student’s t test. No significant differences were shown in anyone of the variables

<table>
<thead>
<tr>
<th>Anthropometric data</th>
<th>ACL injured skiers (n=25)</th>
<th>Skiers without ACL injury (n=314)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genus (male, female)</td>
<td>11 (44), 14 (56)</td>
<td>165 (53), 149 (47)</td>
</tr>
<tr>
<td>Generalized joint laxity (≥ 5p)</td>
<td>4 (16)</td>
<td>34 (11)</td>
</tr>
<tr>
<td>Knee alignment (left), Varus, Valgus</td>
<td>-/ 4 (16)</td>
<td>13 (4) / 19 (6)</td>
</tr>
<tr>
<td>Knee alignment (right), Varus, Valgus</td>
<td>-/ 4 (16)</td>
<td>12 (4) / 25 (8)</td>
</tr>
<tr>
<td>Foot alignment (left), Pes cavus, Pes Planus</td>
<td>-/ 5 (20)</td>
<td>13 (4) / 50 (16)</td>
</tr>
<tr>
<td>Foot alignment (right), Pes cavus, Pes Planus</td>
<td>1 (4) / 4 (16)</td>
<td>16 (5) / 42 (14)</td>
</tr>
<tr>
<td>Leg length discrepancy, ≥ 2 cm (Yes)</td>
<td>1 (4)</td>
<td>7 (2)</td>
</tr>
<tr>
<td>Positive Valgus stress test 30° knee flexion</td>
<td>2 (8) / 1 (4)</td>
<td>47 (14) / 47 (14)</td>
</tr>
<tr>
<td>Anterior knee laxity Side-to-side diff. ≥ 3mm</td>
<td>3 (12)</td>
<td>42 (13)</td>
</tr>
<tr>
<td>Hip flexion with knee extended (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left leg</td>
<td>105 (75-130)</td>
<td>102 (70-138)</td>
</tr>
<tr>
<td>Right leg</td>
<td>104 (80-130)</td>
<td>102 (62-140)</td>
</tr>
<tr>
<td>&gt; 10° side-to-side diff.</td>
<td>2 (8)</td>
<td>30 (10)</td>
</tr>
<tr>
<td>Hip extension with knee flexion in supine position(°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left leg</td>
<td>-8 (-22-10)</td>
<td>-7 (-25-14)</td>
</tr>
<tr>
<td>Right leg</td>
<td>-6 (-20-8)</td>
<td>-5 (-28-20)</td>
</tr>
<tr>
<td>&gt; 5° side-to-side diff.</td>
<td>5 (20)</td>
<td>107 (34)</td>
</tr>
<tr>
<td>Hip extension with knee flexion in prone position(cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left leg</td>
<td>0 (0-10) / 0 (0-13)</td>
<td>0 (0-23) / 0 (0-25)</td>
</tr>
<tr>
<td>Right leg</td>
<td>0 (0-10) / 0 (0-13)</td>
<td>0 (0-23) / 0 (0-25)</td>
</tr>
<tr>
<td>&gt; 5 cm side-to-side diff.</td>
<td>0</td>
<td>21 (7)</td>
</tr>
<tr>
<td>Ankle dorsiflexion with extended knee(°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left foot</td>
<td>39 (30-53) / 40 (32-51)</td>
<td>39 (23-54) / 40 (23-58)</td>
</tr>
<tr>
<td>Right foot</td>
<td>39 (30-53) / 40 (32-51)</td>
<td>39 (23-54) / 40 (23-58)</td>
</tr>
<tr>
<td>&gt; 5° side-to-side diff.</td>
<td>2 (8)</td>
<td>32 (10)</td>
</tr>
<tr>
<td>Ankle dorsiflexion with flexed knee (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left foot</td>
<td>45 (36-56) / 45 (36-57)</td>
<td>46 (29-62) / 46 (25-62)</td>
</tr>
<tr>
<td>Right foot</td>
<td>45 (36-56) / 45 (36-57)</td>
<td>46 (29-62) / 46 (25-62)</td>
</tr>
<tr>
<td>&gt; 5° side-to-side diff.</td>
<td>1 (4)</td>
<td>26 (8)</td>
</tr>
</tbody>
</table>

*a Median and range  
*b Number and percentage
The Cox regression analysis showed a reduced probability to sustain an ACL injury in skiers who had practiced alpine skiing for more than 13 years (p < 0.05) Table 12 / Figure 13.

![Figure 13. The Kaplan-Meier survival curve for number of years in alpine skiing before sustaining an ACL injury](image)

Table 12. ACL injury intrinsic risk factors. Variables with a p-value < 0.20 in a Cox proportional Hazard regression model. Skiers without an ACL injury are defined as a reference group.

<table>
<thead>
<tr>
<th>Intrinsic risk factors</th>
<th>Hazard Ratio (95% CI)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine skiing (years)</td>
<td>0.83 (0.68-1.00)</td>
<td>0.05</td>
</tr>
<tr>
<td>Knee alignment (left), Valgus</td>
<td>2.84 (0.97-8.28)</td>
<td>0.06</td>
</tr>
<tr>
<td>Valgus stress 30° knee flexion (right) Positive</td>
<td>0.21 (0.03-1.19)</td>
<td>0.13</td>
</tr>
<tr>
<td>Functional performance hop tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-leg hop test for distance (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right leg</td>
<td>0.98 (0.97-1.01)</td>
<td>0.08</td>
</tr>
<tr>
<td>Side-to-side difference</td>
<td>0.96 (0.92-1.01)</td>
<td>0.13</td>
</tr>
<tr>
<td>Square hop test (number of correct hops)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side-to-side difference</td>
<td>1.04 (0.98-1.11)</td>
<td>0.19</td>
</tr>
<tr>
<td>Side hop test (number of correct hops) ≤ 5 jumps side-to-side differences</td>
<td>5.19 (0.68-39.67)</td>
<td>0.11</td>
</tr>
</tbody>
</table>
5.2.2 ACL injury - Familiar history as a risk factor

Sixty-five out of 418 skiers, who answered a question about familiar history of ACL injuries, had suffered at least one ACL injury. Among their parents, 51 fathers and 35 mothers had sustained an ACL injury. In ACL injured skiers there was a significantly higher proportion of parents that have sustained an ACL injury when compared to skiers without an ACL injury (p= 0.04).

The results showed an OR of 1.95 to suffer an ACL injury if you have a parent who has had an ACL injury compared to if none of the skier’s parents have had an ACL injury.

There was no significant difference between male and female skiers about their familial relationship.

5.2.3 ACL injury - Previous injury as a risk factor

During the study period 52 ACL injuries occurred. Out of these, 23 skiers reported that they have had an earlier injury in the same knee. A total rupture of the ACL was the most common previous injury (n=12) followed by other ligament injuries located to the knee joint (n=6). Three skiers had an earlier injury in the meniscus, one had a bone bruise, and one suffered from patellar tendinopathy.

5.2.4 ACL injury - Extrinsic risk factors

A total of 52 ACL injuries occurred between September 2006 and May 2013. Fifty ACL injuries occurred during alpine skiing and two during indoor training. Twenty ACL injuries (40%) occurred during the skier’s third year at a ski high school and 15 (20%) during their second year (Figure 14). The majority of the ACL injuries occurred in March followed by November and December (Figure 15).

![Figure 14. Distribution of ACL injuries each year at a ski high school](image)

![Figure 15. Monthly distribution of the occurrence of ACL injuries](image)

Thirty-two out of the 52 ACL injuries (62%) occurred during training. Twenty-six ACL injuries (52%) occurred in giant slalom, 12 (24%) in slalom and nine (18%) in speed disciplines. Eighty-three percent of the ACL injuries occurred in prepared slopes.

The snow conditions were aggressive when 25 skiers (50%) tore their ACL and icy when eight skiers (16%) tore their ACL, loose when seven skiers (13%) tore their ACL and wet
when six skiers (12%) tore their ACL. Twenty-three skiers (46%) sustained their ACL in sunny weather and nine skiers (18%) when it was cloudy. The temperature was between -10 ° and 0° in 35 out of 50 skiers (70%) and at seven injury occasions the temperature was above 0° degree.

Twenty-eight skiers (56%) reported the visibility to be good and 15 that the visibility was moderately good. Twenty-three skiers estimated themselves not to be fatigued at all, and 16 skiers that they were somewhat fatigued at the time of injury.

### 5.3 PREVENTION OF ACL INJURIES

During the control seasons (2006/2007 – 2010/2011) there were 33 skiers (12 males, 21 females) that sustained a total of 35 complete ACL ruptures resulting in a prevalence of 8% and an injury incidence of 0.48 /100 months (95% CI 0.32-0.64) for a skier attending a ski high school. Twenty-four of the ACL injuries were first time ACL injuries and seven were re-injuries. During the intervention seasons (2011/2012 and 2012/2013) 12 skiers (5 males, 7 females) sustained 12 ACL injuries. This resulted in a prevalence of 3.9% and an injury incidence of 0.26 /100 months (95% CI 0.11-0.41) for a skier attending a ski high school. Eight of the ACL injuries were first time injuries and two were re-injuries.

The absolute risk rate showed a decreased incidence rate of -0.22 (CI -0.44-0.00)/100 months for a skier attending a ski high school in favor of the intervention group. A Hazard ratio of 0.56 (CI 0.29-1.08) (Figure 16) was found according to the Kaplan-Meier survival curve. The prevention program reduced the rate of ACL injuries in the intervention group by 45% (RR: 0.55, 95% CI 0.28-1.06).

![Figure 16](image.png)

**Figure 16.** The Kaplan-Meier survival curve for ACL injuries in the intervention group and the control group.
Compliance with the prevention program

The alpine skiers have regularly watched the video 1-10 times. Ninety-four skiers (42%) answered the questionnaire about their compliance. Three out of these 94 skiers injured their ACL during the intervention period.

**Question:** How many times have you watched the video?
75% answered "1-5 times".

**Question:** How much of your training has been focused on equilaterality?
62% answered “it is a part of each physical training occasion” and 20% answered "never".

**Question:** Have you used the suggested exercises from the video to find out whether you can perform equally well with the left as the right leg?
41% answered "yes 1-10 times/month" and 36% answered "never".
6 DISCUSSION

The overall aim of this thesis was to try to reduce ACL injuries in competitive alpine skiers by a specific prevention program based on van Mechelen’s "Sequence of Prevention". All studies involve alpine ski students at the Swedish ski high schools between August 2006 and May 2013.

The first investigation is a five year prospective cohort study presenting the injury profile in terms of injury incidence, injury location, type of injury as well as injury severity among ski high school students. The aim in the second investigation was to study whether there was any relationship between the prevalence of ACL injuries in competitive alpine ski students and ACL injuries in their parents. In the third investigation we tried to identify potential intrinsic and extrinsic risk factors for ACL injuries in competitive alpine ski students. Finally, in the fourth investigation a specific prevention program was implemented in order to try to reduce the incidence of ACL injuries in adolescent competitive alpine skiers.

Competitive alpine skiing is one of our most complex sports, depending on the combination of great physical demands and ever-changing external conditions.

6.1 INJURY PROFILE

The result from the injury profile showed that close to 50% of the skiers attending a Swedish ski high school sustained at least one injury during their study period at the schools. This is alarming because almost all Swedish competitive alpine skiers in this age group have studied at a Swedish ski high school. The highest number of severe injuries in both genders was found in the knee joint and most of these were a ligament injury which is in accordance with earlier publications on alpine skiing at competitive level. No gender differences were found regarding the injury profile, which is in contrast to the publication from FIS ISS system. To our knowledge only a few studies on competitive alpine skiing have been published, which makes comparisons in terms of competitive injury profile difficult. The study design and the injury definition therefore differ between the present investigation and studies by other authors. In the present study all injuries that occurred during both training and competition, which made it possible for the skier to fully participate in skiing or physical training, were recorded including training off-snow over the entire year. In the studies by Bere et al., Bergstrøm et al., Ekeland et al. and Flørenes et al., injury recording was performed during skiing and solely for a part of the year or during a single-event and the injury was defined as an injury that required the skiers to be transported or treated by a medical team. One reason for the study design of the present investigation was to find a total picture of the injury profile in young elite alpine skiers. Alpine skiing on elite level is complex requiring a variety of physical demands. This means that not only injuries during skiing but also during physical training were of great importance. A further reason was due to that a previous injury might be a risk factor for a new injury. About two thirds of the injuries in the present investigation were joint and ligament injuries. These results are in
agreement with the literature when it comes to both recreational and competitive skiers.\textsuperscript{14, 31, 64, 107, 118}

### 6.2 ACL INJURIES

In this study population the prevalence of ACL injury was 15.3\%, which is in accordance with the epidemiological study from one ski high school in Austria\textsuperscript{101} but lower than what Pujol et al.\textsuperscript{100} reported from a French cohort study on competitive alpine skiers. The literature is inconsistent when it comes to gender differences regarding the incidence of ACL injury in competitive alpine skiers. Pujol et al.\textsuperscript{100} and Bere et al.\textsuperscript{14} did not find any gender differences, while Raschner et al.\textsuperscript{101} and Stevenson et al.\textsuperscript{120} reported a twofold increased risk for females compared with males to sustain an ACL injury, which is similar to the findings of the present study. A reason for these variations in the literature might depend on differences in terms of the study populations used. Both Bere et al.\textsuperscript{14}, Pujol et al.\textsuperscript{100} and Stevenson et al.\textsuperscript{120} studied adult alpine skiers, while Raschner et al.\textsuperscript{101} studied alpine skiers aged between 14 and 19 years. Several studies showed similar results that ACL injuries occur in a younger age in female athletes than in their male counterparts.\textsuperscript{2, 85, 128}

An important finding was a significantly higher risk for an elite alpine skier to sustain an ACL injury in the left knee compared to the right knee, which is in concert with Stevenson et al.\textsuperscript{120} and inconsistent with Pujol et al.\textsuperscript{100}

The requirement for an alpine skier is to perform ski turns equally well to the left as to the right. This means that the skier needs the same physical requirements for the left and right half of the body. A possible explanation for the finding in the present study can of course be that the skiers really had a side-to-side difference and/or a dominant leg, which may influence the risk of getting injured. Ford et al.\textsuperscript{34} reported a greater difference in the side-to-side knee valgus motion on the dominant side in uninjured females, but not in uninjured males. Leg dominance has been discussed as a potential risk factor for sustaining an ACL injury.\textsuperscript{19, 73, 82, 106} In recreational skiers Ruedl et al.\textsuperscript{106} reported a twofold risk to injure the dominant knee, while other authors did not find the dominant knee to be a risk factor.\textsuperscript{19, 73, 82} However, Negrete et al.\textsuperscript{82} and Brophy et al.\textsuperscript{19} found a trend that females had a higher incidence of injuries to their left knee, which was not found in males.

### 6.2.1 ACL injuries - Intrinsic risk factors in alpine skiing

Most injuries occurred in the left knee, and it seems like the side-to-side difference when performing the functional tests may play a role of importance.

Furthermore, those who reported a higher number of active years in alpine skiing showed a reduced risk of sustaining an ACL injury. A possible explanation could be that the skiers had a longer period of experiences and therefore more prepared for the performance.

In the present investigation an increased ACL injury risk was found in skiers who performed shorter jumps than those who performed longer ones in the one leg hop test for distance. This hop test is suggested to measure explosive muscle strength, reported to be a characteristic factor of demands in alpine skiing.\textsuperscript{57} Moreover, when performing the one leg hop test for distance a side-to-side difference of 10 centimeter was indicated to be a predictor for ACL injury in the present study. Gustavsson et al.\textsuperscript{41} concluded that the one leg hop test for
distance can discriminate between the injured and uninjured leg in patients with ACL injury. Furthermore, Haitzet al. \(^4\) studied normal values for the one leg hop test for distance as well as for the square hop test, and they did not find a side-to-side leg difference. In view of the published normative data the choice of cut off in the present study, 10 cm of side difference is not too small in order to determine a real side difference.

The side hop test alone and the square hop test alone were not found to be significant predictors of ACL injury. However, unequal performance when comparing the left and right side regarding the hop tests seems to be predictive for ACL injury in this group of skiers. These tests require a more complex movement pattern represented by as well endurance muscle strength as neuromuscular/postural control. \(^5\) In these two hop tests the number of correct jumps is counted irrespective of the quality of the performance of the tests. According to Hewett et al. \(^5\) the knee angle at landing after a jump is important and increased hip adduction and knee valgus have been identified as risk factors for sustaining an ACL injury. The results of the present study indicate that skiers with an increased knee valgus alignment were somewhat more prone to injury than those with a normal knee alignment. When analyzing the performance of the hop tests with respect to alignment and to side-to-side differences valuable information might be found and lead to possibilities for predicting injury risk. The hop tests used in the present study indicated a side-to-side difference to be a predictor for ACL injury. Hewett et al. \(^4\) highlighted the importance of taking the side-to-side difference of the lower extremity into account when it comes to imbalance of neuromuscular control, muscle strength and muscle flexibility. This may probably be of importance in an equilateral sport like alpine skiing, where the same physical demands are put on both legs. Both decreased \(^1\) and increased \(^1\) muscle flexibility have been discussed as injury risk factors. However, to the best of our knowledge there are no reported normal values of muscle flexibility. In contrast to an increased valgus alignment a positive valgus stress test seems to decrease the risk for sustaining an ACL injury. An explanation could be that a clinical test differs from a functional performance test. It could be hypothesized that tests for neuromuscular control are more important from a functional point of view than a clinical stability test of the knee joint. By analyzing the hop tests with respect to alignment this might give us an indication of injury risk. Another reason could be that a positive valgus stress test means that the knee is lax in medio-lateral direction and could thereby help the skier to perform an increased range of motion before an injury occurs. However, a higher percent of the ACL injured skiers than those without ACL injury presented with a side-to-side difference in all three functional performance tests.

The present study showed that an alpine ski student at a ski high school is almost twice more likely to sustain an ACL injury if he (or she) has a parent with an ACL injury when compared to ski students without a family history of ACL injury. This is in accordance with earlier publications. \(^3\), \(^4\), \(^5\), \(^6\) This is the first study including a homogenous group, recruited as a cohort from the same sport, This is in contrast to other studies that have included different sports. \(^3\), \(^4\), \(^5\), \(^6\) A study by Anderson et al. \(^4\) is the only study where no relationship was found between family history and ACL injury. However, a problem when comparing these studies is that the definition of the family member is unclear. Harner et al. \(^5\) included family members, while Hewett et al. \(^5\) found a familiar risk when they studied sisters in one family. Myer et al. \(^6\) used the definition of first degree relative but did not define what they mean by
that, while Flynn et al. 33 define the first degree relative as someone whom they shared 50% of their genetic make-up with.

A series of publications 96-99 relating genetic factors have shown that genetic factors predispose subjects to an ACL injury, but one of these studies 98 on female soccer players did not show any generalization to males or other populations. The results of the present study showed a higher tendency to suffer an ACL injury if the skier has a mother who has had an ACL injury than if he/she has a father with a previous ACL injury. However, this result was not statistically significant, which may depend on too few cases.

The cohort, adolescent competitive alpine skiers, belongs to a group of athletes that are exposed to high risk of ACL injuries. The data collection in the present study was performed through a questionnaire, and is in agreement with methods used in earlier studies. 33,46

When it comes to injury occurrence the impact of heredity and environmental factors is an ongoing discussion without a definitive answer. However, it is important to take every possible opportunity to identify risk factors for suffering an ACL injury in competitive alpine skiers. Knowing that a skier with a family history of ACL injury, defined in this study as having a parent that has sustained an ACL injury, means that he/she is twice as likely to suffer a knee injury. However, this information is not easy to communicate to their children and may not have any impact on their behavior, as it would be unethical not to allow children/adolescent to ski because he/she has a parent who has had an ACL injury. On the other hand it would be unethical not to recognize this knowledge. The first step may be to ask questions about familial relationships regarding ACL injuries in order to identify the adolescents at increased injury risk. It is suggested that individuals with a possible predisposition for an ACL injury should be especially careful and observe safety precautions of external risk factors for not exposing themselves to unnecessary risk situations. From a clinical point of view a further suggestion could be to introduce and highlight preventive strategies for the risk to sustain a severe knee injury.

In contrast to earlier studies on ACL injury risk factors 44,65,92 previous lower extremity injuries were not found to be a significant risk factor in the present investigation. However, in the present study ski students with an ACL injury prior to the start of the study were excluded leaving only other previous injuries to the lower extremities than ACL injury as potential risk factors. When including the skiers with an ACL injury, lower extremity injuries were found to be a significant risk factor consistent with the literature (unpublished data). From the injury profile we found no differences, regarding time to the first injury between those skiers that had an ongoing injury and those that were uninjured at the start of the study. When the skiers, which sustained one injury, two, three or four injuries were divided it was found that the sooner the first injury occurred, the risk of sustaining another injury increased. It is likely, although not evidence based, that this finding underlines the importance of a proper rehabilitation and to be fully recovered before returning to skiing after an injury.

### 6.2.2 ACL injuries - Extrinsic risk factors in alpine skiing

In only a few studies evaluation of extrinsic risk factors in competitive alpine skiing has been performed. From an interview study including 61 expert stakeholders Spörri et al. 115 reported 25 key injury risk factors. Ski equipment (boot, binding, plate) was ranked as number one and
physical aspects were ranked as number four and suggested to be more investigated. Furthermore, the experts believed that the icy conditions would be safer than aggressive snow conditions, which is consistent with the present study as well as with Bere et al. \(^{13}\) An interesting finding was that most ACL injuries occurred during the skiers’ second and third study year. A reason for this could be stress related, because most of the skiers who have reached the highest level in alpine skiing also have been successful as juniors. \(^{109}\)

In the present investigation the majority of the ACL injuries occurred during training. This may be due to that the slopes were not as well prepared as they usually are during competition. A larger effort to achieve a safe course is likely to be an injury prevention factor. The technical disciplines giant slalom and slalom account for 38 out of the 52 ACL injuries. This is in accordance with Gilgien et al. \(^{39}\) but in contrast to earlier studies \(^{14,31}\), where downhill race accounted for the highest number of injuries. In the present study no calculations of ACL injuries between the different ski disciplines were carried out, which may explain the contradictory results. However, it is assumed that the volumes of training and competition are similar between the different Swedish ski high schools and the different disciplines. Another possible explanation may be change of rules. During this study period only small changes of rules have occurred and this therefore probably does not influence the occurrence of injury in the different disciplines.

### 6.3 Prevention of ACL Injuries

The principal finding in study IV was that a prevention program reduced the overall rate of ACL injuries by 45% in alpine ski students attending a Swedish ski high school.

To the best of our knowledge the present investigation is the first one in adolescent alpine skiers at competitive level. Out of previous studies evaluating ACL injury prevention only one studied alpine skiers, \(^{27}\) but in recreational skiers. Ettlinger et al. \(^{27}\) reported a decreased ACL injury rate as a result of a special educational program in order to avoid ACL injury risk situations, like how to fall when off balance and how to stop after a fall. In accordance with Ettlinger et al. \(^{27}\) the authors of the present study have tried to teach both the ski coaches and the skiers to be aware of possible ACL injury risk situations. Awareness of certain risk situations may help to reduce the skier’s technical mistakes and thereby preventing an ACL injury. \(^{13}\)

The difference between recreational skiers and competitive skiers is due to that a recreational skier can choose his/her own course, while a competitive skier is skiing in an already prepared course. Few studies on injury prevention in alpine skiing exist and most of them include recreational skiers and are studies on the use of helmet. \(^{9,42,43,70,76,121}\)

Alpine skiing is an equilateral sport meaning that the same physical demands are put on both legs. Unpublished data have shown that ACL injured alpine skiers had an increased side-to-side difference when performing the one leg hop test for distance compared to uninjured skiers. The side-to-side difference may at least to some extent explain why the skiers’ left knee was more often injured than their right knee. A recent publication about normative data when performing hop tests showed various results in terms of the best leg (left or right) for hop performance. \(^{53}\) When it comes to the one leg counter movement jump, hop performance of the dominant leg was superior to the non-dominant leg. \(^{53}\) Contrary, in the one leg stability
test the performance of the non-dominant leg was superior to that of the dominant leg. Alpine skiing is a multifactorial sport including a number of different physiological demands on the skier. Therefore, the goal of the prevention program in the present investigation was to perform different types of exercises, indoors as well as outdoors on snow, with focus on how to perform equally well on the left and right leg. In female athletes it has been reported that those with a side-to-side asymmetry in terms of muscle strength are at a greater risk of injury than athletes without this asymmetry. Whether this goes for male athletes, as well is, however, not known. Moreover, Hewett et al. have pointed out the importance of a good neuromuscular balance between the quadriceps and hamstring muscles, the dominant and non-dominant leg and a good postural control in order to prevent ACL injuries. These aspects are probably of potential interest especially in an equilateral sport like alpine skiing. Likewise found Raschner at al. pore core stability to be a critical factor for ACL injury in competitive skiers attending a boarding school.

The somewhat sparse compliance to the suggested exercises may not explain the reduced number of ACL injuries in the intervention group. An explanation of the low compliance among the skiers might be that they did not understand that neuromuscular exercises to reach the same performance of both legs were suggested in order to prevent ACL injuries. Finch et al. concluded that a prevention program must be carried out regularly and be integrated with the normal sport specific training. This is what has been taken into account in the present investigation. Unfortunately, the sample of the study group was somewhat small in order to do group analyzes of high compliance and low compliance, which could be of interest in future studies. This means that other factors might have been more important. From a psychological point of view the close contact between the principal test leader and the coaches and their alpine skiers throughout the entire study period might have played a more prominent role.

Sport performance is synonymous with success in the sport. The optimal prevention program should be designed not only to prevent injury, but also to increase performance. Combined performance and prevention training could be instituted with a higher potential for coach and athlete adherence. Moreover, it should be kept in mind that a sports-related injury may have several causes, and all injuries can not be prevented. The However, it is likely to believe that the use of sports injury prevention strategies may reduce the number of injuries and/or injury severity.

6.4 METHODOLOGICAL CONSIDERATIONS

Despite the large prospective cohort design of the present thesis, there are a few limitations to take into account while interpreting our results.

Time of exposure is an overall methodological consideration. Most studies report time of exposure in hours during practice and game or competition. In alpine skiing the number of runs also has been suggested. Since the slopes vary in length and a run may vary in time the use of runs as time of exposure might be misleading. In the present thesis the number of months that a skier attended a ski high school was chosen to represent time of exposure. The reason for this choice was that all schools have approximately the same schedule with respect to practice, competition and ski camps.
Study I: A study limitation is that injury location and not the specific injury diagnosis, except for ACL injury, was reported. Mild injuries that did not need to be treated by a physician could thus not be diagnosed. Only ACL injuries were properly diagnosed by sports orthopedic surgeons.

Study II: The questionnaire used in this study was not tested for reliability and validity, which is another limitation of the study. A further study limitation is lack of access to the injury records regarding the ACL injuries of those parents that had had an ACL injury. Moreover, this also led to lack of information about whether the ACL injuries of the skiers’ parents were sports-related or not, and if this was the case, in what sport.

Study III: The clinical tests and functional performance tests were not completed in a laboratory due to very different geographical locations of the ski high schools. To be able to include all Swedish ski high schools, the tests had to be performed at each specific ski high school. The reliability of these tests has been published earlier and to minimize possible measurement errors the present study used one test leader (MW) with good intratest-retest reliability. However, the complex interaction between different types of variables makes the study design of injury risk factors somewhat complicated. Finch 28 as well as Bahr and Holm 6 have recommended prospective cohort studies with multivariate statistical approaches in order to detect injury risk factors within the area of sports medicine. Twenty to 50 injury cases are suggested for a moderate to strong association, and the choice of the participants should be representative for the actual sport. Dallinga et al. 21 have recommended to use a prospective design in different age groups, which is similar to the present study including almost all Swedish competitive alpine skiers in the age group 16-20 years. Despite, the large sample size of the present investigation the occurrence of ACL injuries did not allow a multivariate regression analysis or separate analysis of injury risk factors with respect to gender. Such an analysis might have shown different injury risk factors for male and female skiers, since physical performance and muscle flexibility may vary between genders.

Study IV: The use of historic controls might be seen as a study limitation. The reason for using historic controls was twofold, though. The alpine ski students from the different ski high schools are regularly meeting each other at both national and international ski camps and ski competitions. Consequently, it was impossible to randomize some of the skiers to one intervention group and others to a control group without the risk of a crossover effect. Furthermore, due to the limited number of alpine ski students in Sweden, the use of historic controls was the way of being able to perform a controlled prevention study of this type. More alpine ski students and/or a higher number of studied ski seasons could possibly have been more appropriate. However, it should be pointed out that the present study was based on a cohort consisting of all Swedish alpine ski students including more than 200 students per year. In addition, the students are solely studying three or four years at a Swedish ski high school. Subsequently, to increase the number of skiers and/or ski seasons could result in some logistical problems.

The present thesis was thus based on four studies with observational design including a homogenous cohort of adolescent competitive alpine skiers. The main strength of the thesis is the prospective design with a large sample size, as has been recommended in order to minimize recall bias. 6, 28, 130 Another strength when using the prospective cohort design is
that you are able to calculate the absolute risk. The absolute risk, associated with exposure, is of greater interest than the relative risk. It provides the researcher with information to make it possible to evaluate the overall risk of being injured at different levels and across sports by using the absolute injury rate.
7 CONCLUSION

- The injury incidence rate in competitive alpine skiing was found to be 1.7 injuries/1000 skiing hours or 3.11 injuries/100 months’ attending a ski high school. No gender difference in terms of injury incidence was shown.

- Nearly 50% of alpine ski students sustained at least one injury during their study years at a Swedish ski high school. The highest number of injuries was located in the knee joint for both male and female skiers, and ligament injuries were the most common ones.

- Almost half of the injuries were considered to be severe, while most other injuries were classified as moderate.

- An alpine ski student is almost twice more likely to sustain an ACL injury if he (or she) has a parent that has had an ACL injury when compared to an alpine ski student without a family history of ACL injury.

- One third of the knee injuries were represented by ACL injuries. Female skiers showed a higher risk to sustain an ACL injury compared to male skiers. Two thirds of the ACL injuries occurred in the left knee.

- Of the studied potential risk factors, no one was identified as an ACL injury risk factor. A side-to-side difference of functional performance hop tests was found in those skiers that sustained an ACL injury.

- Skiers with a higher number of active years in alpine skiing had a reduced risk of sustaining an ACL injury.

- The majority of the ACL injuries occurred when the skiers’ studied their third year at a ski high school, and most injuries occurred in March. More than half of the injuries occurred during training and most often in the technical disciplines. The snow conditions were aggressive and icy in two thirds of the injury occasions. The weather was sunny in almost half of the injury occasions.

- The prevention program showed a 45% reduction of the ACL injury incidence rate during the intervention period in comparison with the control period.
8 FUTURE RESEARCH

Future studies on competitive alpine skiing are warranted. A number of publications regarding recreational skiers exist, while there is a lack of studies on competitive alpine skiers.

The results from the present thesis revealed a large number of injuries in adolescent competitive alpine skiers, especially ACL injuries. This indicates the need for future research within this field.

More advanced laboratory evaluation instruments could improve identification of alpine skiers at risk for an ACL injury while skiing. Competitive alpine skiing puts high demands on thigh muscle strength. Therefore, adding isokinetic measurements of knee extensors and knee flexors to physical performance tests might further improve identification of skiers at risk for ACL injuries. Furthermore, the counter movement jump may be a suitable hop test since it has been suggested to be associated with sporting results in at least male but not female competitive alpine skiers. To the best of our knowledge no study about ACL injury risk factors comparing male and female skiers has been performed. This is a further subject of potential interest because of gender differences during growth and maturation.

Another area of study within alpine skiing could be to control the skier’s adjustments of bindings during the season. This has been suggested by Spörri et al., who found the ski-binding-plate-boot to be the number one key risk factor for ACL injuries.

Moreover, it would be interesting to add the suggested two further steps in the TRIPP model by Finch The goal of a possible fifth step in injury prevention would be to study the context regarding the athletes’ and their coaches’ barriers. Finally, in a sixth step, to evaluate injury preventive strategies in a larger real context such as implementing the prevention program to younger skiers. Based on these steps our research group recently has conducted an interview of alpine ski coaches using a qualitative approach in order to capture the experiences from the coaches’ perspective. Hopefully, that study may provide us with information on how to increase the compliance of preventive strategies among alpine skiers, before implementing the prevention program in a real world context.
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