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List of Abbreviations

| BIAD | boot induced anterior drawer |
|------|--|
| BW | body weight |
| CoM | centre of mass |
| CoP | centre of pressure |
| CNS | central nervous system |
| 3D | three-dimensional |
| DIN | Deutsches Institut fuer Normung |
| DoF | degrees of freedom |
| DLT | Direct Linear Transformation |
| FL | 'flexible' boot condition (study III) |
| GPS | global positioning system |
| GRF | ground reaction forces |
| GRM | ground reaction moments |
| IAS | International Organisation for Skiing Safety |
| INS | inertial navigation system |
| ISO | International Standardisation Organisation |
| IMU | inertial measurement units |
| NS | 'no shaft' condition (study II) |
| PDA | personal digital assistant |
| ST | 'standard' boot condition (study III) |
| TLEM | Twente Lower Extremity Model |
| WS | 'with shaft' condition (study II) |

Glossary

| Aerial | Ski Jump |
|-------------------------|---|
| Absorbing | compensating a mogul by bending the legs followed by immediate straightening of the legs in order to retain snow contact |
| ACL rupture grade I-III | An anterior cruciate ligament injury is extreme stretching or tearing of the anterior cruciate ligament (ACL) in the knee. A tear may be partial (grade I or II) or complete (grade III). |
| Angulation change | in ski turns the upper body and the lower body always approximate laterally in the frontal plane; angulation change means the lateral motion changing from one angulation to the other |
| Acrobatic | Artistic ski dance |
| Back seat | distinctive backward lean position of the body |
| Big air | Big jump combining different elements resulting in a spectacular performance (e.g. flips and twists) |
| Canting settings | adjustment of the ski boot shaft angle in the frontal plane with respect to the boot sole |
| Down-unweighting | trying to take the weight off the feet for a short time period by rapidly bending the legs |
| Edging | using the sharp edges of the skis to avoid slipping and thereby to retain speed control |
| Fakie | riding or landing backwards (facing the mountain) |
| Falling-inward | side lean of the CoM towards the inside of the turning curve with respect to the skis while remaining dynamic balance, refer to CoM of the skier with respect to skis |
| Fat boys | wider skis for deep snow |
| FIS | Federation International du Ski (International Ski Federation) |
| Half pipe | Man made trough of snow for jumping |
| Inverted aerial | Off-axis rotation / upside down movements during a jump |
| Inverse dynamics | derives the kinetics responsible for the investigated movement; from observations of the motion (of limbs), inverse dynamics is used to compute the associated moments (joint torques) that lead to that movement, under a special set of assumptions |
| ISS | Injury Surveillance System |
| Kinematics | (Greek <i>kinein</i> , to move) describes the motion of objects without the consideration of masses or forces |

| | that bring out the motion |
|------------------|--|
| Kinetics | (Greek <i>kinesis</i> , movement) describes the act of moving \rightarrow forces and interactions that produce the affect of motion |
| Moguls | Snow bumps (either artificially or naturally built on a relatively steep slope) |
| New school | In skiing: stylish tricks and spectacular jumps currently dominating skiing magazines and freestyle films |
| Normal GRF | perpendicular acting GRF that are not acting vertically due to the slope inclination |
| Off-pist skiing | skiing in the backcountry off the marked slopes |
| Neutral position | The neutral position is defined to be a middle position with regard to the antero-posterior direction, with the body's centre of mass above the base of support |
| Rails | Obstacles to slide over |
| Ski cross | Group race with four to six competitors |
| Slope style | Combination of rails and jumps |
| Up-unweighting | trying to take the weight off the feet for a short time period by pushing the body up from the legs |
| V-position | adjustment of the ski boot angle in the horizontal plane |
| | |

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Chapter 1: Introduction

1.1 Relevance of the project

Alpine skiing is one of the most popular leisure activities with approximately 200 million skiers worldwide. Since the development of glacier ski fields it is now possible to participate in snow sports regularly even during summer time (Harrer, 2000). Today, recreational skiing serves certain necessities corresponding to social, cultural and economical conditions. Skiing provides an ideal respite for a sedentary lifestyle for many people by providing physical fitness, psychological well-being as well as fun and recreation in a natural environment (Everard, Hudson, & Lodge, 2004).

With freestyle skiing disciplines, namely *moguls* and *aerials*, now permanent components of the Winter Olympic Games, there is an increased interest of these among recreational skiers. It can be speculated that broadcasted reports on international competitions provide advanced skiers with new role models or that simply an increased skill level of recreational skiers supports this trend. In addition to requiring diverse technical skills beyond those involved in traditional alpine skiing, it is likely these disciplines produce different loading patterns due to extreme body postures and repetitive impacts. Through observation, these movement and loading patterns are potentially critical with regard to risk of injury. Skiing and snowboarding in New Zealand resulted in 17,286 snow sport injury claims over the 2009-2010 period, leading to a total cost of NZD 19,775,833 for the Accident Compensation Corporation (ACC) (ACC, 2010). It has been noted that the knee is involved in the majority of freestyle skiing injuries (Heir, Krosshaug, & Ekeland, 2005; Inoue, Samukawa, Ohnishi, Ishibe, & Yasuda, 2006; Koehle, Lloyd, & Taunton, 2002; Krosshaug, 2002; Krosshaug, Heir, Hallingstad, Engebretsen, & Bahr, 2002; Maes, Andrianne, & Rémy, 2002). Worldwide, approximately 100,000 serious knee injuries are caused by skiing every year. This leads to a cost of 1 billion USD for rehabilitation and repair (Hunter, 1999). These statistics display the health and fiscal importance of the identification of potential risk factors and the development of injury prevention strategies in freestyle skiing. Equipment innovations demonstrated in the current work within this thesis are relevant within this context.

Skiing is often subject to changes with regards to equipment, techniques and instruction guidelines, marked by the dynamic characteristics of this sport. Innovations such as

modified skis, ski boots or techniques have been discussed controversially in terms of injury risk (Schaff, Schattner, & Hausel, 1987; Schwameder, Nigg, Tscharner, & Stefanyshyn, 2000; Senner & Lehner, 2006). Due to the widespread interest in skiing worldwide as a recreational and competitive sport, skiing is being investigated by researchers in areas such as biomechanics, engineering, physiology, psychology and sociology. Prospectively, researchers will investigate the options for, on the one hand, improving training efficiency and on the other hand, investigating injury prevention (Mueller, 1987). However, in the scope of biomechanics, field tests are costly with regards to money requirements, time consumption, need of high quality measuring devices, the appropriate environment and participants able to manage the complex set ups. As a result no quantitative research has been published on the mechanics of freestyle skiing to date. With a better understanding of biomechanical parameters and an enhanced knowledge of the relationship between equipment properties, movement restrictions and joint loadings appropriate action can be implemented. Due to this many injuries could potentially be avoided. Hence this project is the first to investigate three-dimensional (3D) joint loading in freestyle skiing.

The work in this thesis aims to assess the effects of equipment modifications on kinetic and kinematic variables in the specific discipline of mogul skiing. Potential areas for improvement will be identified thereby providing the framework for reducing the high rate of knee traumas.

1.2 Background on skiing

1.2.1 Historical Overview

Traditional alpine skiing has a long history. Precursors of modern skis have been found in Scandinavia and Siberia dating back to 2,000 $_{BC}$ (Hunter, 1999). Originally, skis are believed to have been used by fishermen and hunters as a means of transport to prevent the foot from sinking into deep snow. Competitive skiing seems to have its roots in Norway where in 1767 a military competition resulted in people from Scandinavian countries using skiing as a mainstream activity (Hunter, 1999).

The Czech Mathias Zdarsky is deemed to be the first skiing instructor in Austria, where modern alpine skiing techniques originated (Heller, 1978). A winter sports week as a part of the 1924 Paris Olympics helped to present skiing as a sport, moving away from its rather traditional use as a transporting or leisure activity. This was aided by the creation of

the International Ski Federation (FIS) in the same year. However, only the Nordic disciplines of cross-country skiing, ski jumping, and the combined Nordic - a combination of the two - were included in the Olympic Games. In 1931 the first World Skiing Championships were held in Muerren, Switzerland and in 1936 alpine skiing was incorporated into the Olympic Winter Games of Garmisch-Partenkirchen, Germany. Skiing's new lease of life after World War II was encouraged through this newly founded competition (Pfister, 2001).



Figure 1: Zdarsky 1900.

The Olympic disciplines of skiing are now divided into cross-country skiing, ski jumping, Nordic combined, Alpine skiing and freestyle skiing. All these disciplines are subdivided into further specific disciplines. Alpine skiing, in our modern society, is a popular leisure activity for the general public for reasons described above. Its popularity is illustrated by a great audience following the competitions on television throughout the world. As society, social norms and behaviours steadily develop and change, so does skiing equipment and accordingly techniques. This will be outlined within this introductive chapter.

1.2.2 Skiing Equipment

The incentive behind the evolution of sports equipment is functionality, which corresponds to constantly changing demands imposed by society (Pfister, 2001). There is a perpetual competition with regards to snow sport equipment and therefore a persistent necessity of innovation which corroborates economical importance. The health

V=v List of research project topics and materials

importance, as the other major aspect regarding equipment developments, will be discussed in subsequent chapters (Chapter 2). Skiing equipment, its history and its current state will be presented in the following sub sections.

1.2.2.1 Skis

Approximately 4000-5000 years ago skis were a piece of wood under each foot used as for mobility in snowy environments. Later, skis became customized to different types of activities such as the requirement for equipment to cover distances within an Alpine environment for both competitive and recreational purposes. At the same time new shape, material and manufacturing methods developed. Until the 1960s skis consisted of a plank of wood, produced with stone tools with the most commonly used materials being ash and hickory wood causing a high risk of injury (Soltmann, 2005). The development of fibres and technologies using composite materials were implemented in the skiing industry in the 1970s, eventually leading to improvements in elasticity, sustainability and the breaking resistance of skis. The 'carving ski' or 'shaped ski' revolutionized the ski industry in the 1990's. Skis became shorter with a small waist width and wider tips and tails. Furthermore, sophisticated improvements of damping properties have been developed recently (Hosokawa, Kawai, & Sakata, 2002). These features simplified carved turns along the edge of the ski.

Skis are typically symmetrical. Carving skis for adults usually measure between 150 cm and 180 cm and have up to seven different layers of fibre, a wooden and/or foam core and metal edges (Figure 2).



Figure 2: Ski anatomy, a) different ski parts; b) ski core; c) ski edges (Spadout, 2005).

Skiers of different disciplines have different preferences and due to this ski types exist in various designs (Figure 3). For instance, short skis with a narrow waist and a small radius aid turning initiation and allow for quick, sharp turns. This is advantageous for slalom racing which requires more balance. On the other hand, stiff skis with a larger radius are beneficial for giant slalom. Wide skis - or 'Fat Boys' - provide more surface area and thus the needed buoyancy in fresh powder snow (Figure 3,a). However, these skis also have a relatively wide waist and are slower when the skier attempts to put it on the edge. Allround Carvers can be used for general purposes in all kind of terrains (Figure 3,b), Lady Allmountain skis are for women and often used for 'off-piste skiing' (Figure 3,c). Freestyle equipment differs slightly from normal alpine skiing equipment. Freestyle skis are a group of specialized skis, each of which are designed for a specific discipline. The so-called 'twin tips' have the same geometry from the centre line to the shovel and tail (Figure 3,d) and are preferred for backward landings in 'slope style' (chapter 1.2.3.1). Mogul skis (Figure 3.e) usually have no or a minimal side cut and are narrower since using the edges is not as important as for carving or slalom. Instead, mogul skis are stiff behind the binding and more flexible towards the tip in order to enable the skier to keep a stable body position and absorb the forces due to mogul skiing (chapter 1.2.3.1).

When leaning to one side while skiing at a certain pace, the ski bends allowing the skier to turn at the 'natural' angle provided by the ski's side-cut radius. The side-cut of the ski indicates the radius followed on the effective edge, which commonly ranges from 10 to 15 meters depending on the ski length. Profile dimensions provide information regarding the shape and width of a ski and are indicated as 'shovel (tip) width – waist width – tail width'. Most dimensions are indicated in millimetres (mm). The general rule is 'the longer the ski the greater the radius'. The choice of ski length, side cut and stiffness of the ski are subject to specific weight ranges and rider heights as well as preferences and skills of the skier.



Figure 3: Various ski types, a) Powder Ski, b) Allround Carver, c) Lady Allmountain, d) Twin Tip, e) Mogul Ski.

1.2.2.2 Poles

Ski poles have evolved from two origins: It was used to maintain balance with poles being developed from a spear with a basket added at one end and used as a walking stick. Double poles were used to reach a higher speed on skis in addition to supporting turning rhythm and balance. They consist of grips and straps that tighten around the wrists on the upper end. At the bottom end the pole shaft and the spiked tips with a small basket prevent sticking too deep in the snow. The general rule for choosing the correct pole length suggests a 90° angle between upper arm and forearm when holding the pole (Spadout, 2005). Ski poles are available in different widths and can be semi-flexible to stiff. They commonly measure between 110 cm and 140 cm for adults. Poles for mogul skiing are chosen 10cm shorter than usual, as the pole is set on the mogul when the skier is in the valley in front of it (chapter 1.2.3.3).

1.2.2.3 Ski Boots

Ski boots are specialized footwear for skiing and were originally made of leather. The development of ski boots increased with the popularity of the sport and therefore there have been innovations in skis over the last four decades (Hunter, 1999; Johnson, Ettlinger, & Shealy, 1989). Thus in the late 1960s first attempts were made to produce

a plastic boot with a higher shaft that protects the ankle (Casper, 1996). Presently, ski boots are categorized as Alpine Skiing, Nordic Skiing and Alpine Touring boots.



Figure 4: Ski Boot.

Alpine Ski boots have rigid soles and attach to the binding at both, the toe and heel. The boot shells are tightened up by three to five buckles (Figure 4) and are available in various degrees of stiffness indicated by so-called 'flex' values. The liners are either thick and soft or thin and hard and they can be moulded to the individual's foot to assist in the fitting. Some modern ski boots are equipped with additional features such as 'Canting' or the 'V-position', which describes the adjustment of the ski boot angle in the frontal or the horizontal plane, respectively, for a more precise adjustment of the body posture during skiing. Standards for ski boots are determined by the International Standardisation Organisation (ISO) (Heir, Dimmen, & Ekeland, 1999). Ski boots are deemed to be the most important piece of equipment to be chosen by the skier, because they need to fit the individual foot for comfort.

1.2.2.4 Bindings

The bindings are a necessary piece of safety equipment attaching the ski boots to the skis and thereby it completes the skier-boot-binding-ski system. Previously, leather boots were strapped onto the ski. Modern ski bindings consist of a heel piece and a toe piece. To increase safety bindings are now required to release on either side. The binding can release through application of a force that pulls up the heel or a certain amount of torque that twists the toes sideways which usually happens as a result of a fall (Pfister, 2001).



Figure 5: Parts of a modern ski binding (Summitsportsinc, 2009).

The amount of torque that releases the boot is regulated by a DIN setting, which can be adjusted using a screw driver. It is based on the skiers weight, height, ski boot sole length, skill and age. In general, there are specific types of bindings for different types of skiing, such as Alpine, cross country, Telemark, Alpine ski touring and non-release bindings for snowblades. The most commonly used Alpine bindings have a snow brake that prevents the ski from slipping whilst not fixed to the boot. Ski bindings for carving skis are commonly provided as an integrated binding system with binding plates as they increase the edge angle and thus allow for a greater leaning angle. However, powder or freestyle skis are not equipped with this additional feature since a greater edge angle is not desired for these particular techniques. The following sub-section outlines the substantial demands of freestyle skiing.

1.2.3 Freestyle Skiing

1.2.3.1 Development of freestyle skiing

In 1907, the first photographs of flips on skis were taken. Some creative and adventurous skiers have transcended the boundaries of conventional skiing, attempting to invent new ways of skiing rather than to perfect current certain style. The advancement of freestyle skiing occurred around the 1960's. The media began to pay attention to freestyle skiing in the USA when the first professional competition took place in 1971 (Fry, 2007).

Freestyle skiing in its infancy, formerly known as 'hot-dogging', involved virtually anything outside of the strict disciplines imposed by traditional skiing. The Austrian skiers, Kastner and Garhammer, launched a ski circus in 1973 named 'International Perfect Ski Artists' (IPSA). The International Freestyle Skiers Association (IFSA) was established in 1973 and initially aimed to standardise competition rules and safety control. The FIS accepted freestyle skiing as a sport in 1981 and several nations incorporated it in their national instruction guidelines (Casper, 1996). In 1986, the first Freestyle World Championships were held in Tignes, France, which indicated a breakthrough for freestyle skiing in Europe and the world. Subsequently the International Olympic Committee (IOC) featured mogul skiing at the 1988 Calgary Winter Olympics as a demonstration sport. At the Albertville Olympics in 1992, Edgar Grospiron was the first athlete to win a gold medal in mogul skiing. Media coverage of mogul skiing increased worldwide and tickets for the freestyle events at the Olympic Winter Games in Lillehammer 1994, Nagano 1998, and Salt Lake City 2002 were sold out months in advance (Nankoo, 2004). Mogul skiing gained more popularity since the reintroduction of inverted aerials in 2003/2004 after they had been banned from official competitions in 1976 following serious injuries to skiiers (Fry, 2007). Since then, jump styles changed and opened a path for the 'New School' era. The 'New school' era encompasses stylish tricks and spectacular jumps and currently dominates skiing magazines and freestyle movies (Babic, Bloechl, & Bloechl, 2006; Fry, 2007).

1.2.3.2 The Disciplines

Freestyle skiing covers the disciplines of aerials, half-pipe, acrobatic-ski, big air, ski-cross and moguls. They are all disciplines of the FIS except for acrobatic and big air. Moguls and aerials are permanent components of the Olympic Winter Games.

- For the event of aerials, there are several kickers for different kinds of jumping manoeuvres (e.g. single, double or triple flips). All athletes complete two jumps with different levels of difficulty and are judged based on their take-off, height, length, performance and landing characteristics.
- Half-pipe skiing is carried out in a man-made trough. Scoring criteria vary but are generally based on amplitude gained above the lip, technicality of the trick performed, execution, and overall impression of the entire run.
- Acro-ski as a freestyle discipline is related to the area of dance judged on difficulty and artistry. Acro-ski predominantly consists of different combinations of dance steps, twists and acrobatic jumps performed to music in a graceful manner in a flat terrain.

- Big Air participants show one jump combining different artistic elements.
- Ski-Cross is a group race with four to six persons simultaneously racing down a course similar to a bob sleigh. Physical contact is prohibited and scoring is based only on the finishing time.
- Mogul contestants have to successfully get down a slope with bumps while judges give points for speed, technical execution and two compulsory jumps (International Competition Guidelines, 1996). Since the focus of the current thesis is on this particular discipline it will be presented in more depth in the following paragraph.

1.2.3.3 Mogul skiing

Moguls are series of bumps found usually on steep slopes, that can be generated intentionally (with shovels or machines), or unintentionally (by skiers grinding groves into the snow). Competitive mogul skiing involves manoeuvring down a hill of 25-35 degrees inclination and 230 m to 270 m with bumps approximately 3.5 m apart. The competition course consists of a straight run down with up to 1.2 m high bumps and two jumps placed approximately 50 m from both the starting line and the finishing line, respectively (Figure 6,b). The scoring contains judging of jumps (12.5% each), speed (25%) and mogul skiing technique (50%) (Nankoo, 2004). For a good technique mogul skiers have to maintain snow contact and absorb the bumps quickly while the upper body remains steady and moving in a straight line (Figure 6,a).



Figure 6: a.) Mogul skier: b.) Jump in a competition mogul slope.

During a mogul run the skis should stay together in order to act synchronously. The essential movements are the bending of the legs to absorb the mogul and the active extension of the legs immediately after crossing the mogul so as to push the ski tips into the next dip. The poles are set alternately onto the mogul very quickly and should remain

in front of the body to avoid inefficient movements with the arms. The desired line to ski is between the moguls, which is easiest at moderate speeds (Figure 7,a). An alternate option is to go directly over the moguls, which requires the greatest bending movement and the risk of not retaining snow contact causing a 'slingshot' at a higher speed (Figure 7,b) leading to repetitive impacts on the top of the moguls without control. Hence the amplitude and frequency of the bending and extending movements need to be adjusted according to the shape and height of the moguls and varying speed (Ofner, 2006). The most efficient method to ski down a mogul course is a compromise between these two options, specifically pointing the rising edge of each mogul on the side in order to retain snow contact and thereby controlling the speed to still be able to initiate the next turn quickly.



Figure 7: Different tracks to go through moguls: a) around the moguls through the dips; b) over the moguls.

The environmental challenges in mogul skiing are high compared to skiing on groomed slopes and the difficulty varies depending on shape, steepness and consistency of the moguls. Mogul skiers need to react quickly and adjust their position within a limited time frame and their degrees of freedom are reduced since they have to cope with a unevenness. It is therefore more challenging to finely-adjust the physical skills with the environmental demands, especially as most ski resorts lack mogul slopes of variable difficulty and these often exceed the difficulty of the average recreational skier (Brandauer, Felder, & Senner, 2009).

1.3 Summary

Alpine skiing in general has noticeably changed with regard to function, intention, technique and equipment since its early beginning. The increasing popularity of freestyle skiing within the last 40 years and its acceptance as a discipline and incorporation in the

program of the Olympic Winter Games led to a growing demand for scientific studies in this particular area. Freestyle skiers typically show differences in movement patterns characterized by more dynamic movements and artistry with more impact situations. The following chapter will introduce skiing-related injuries including epidemiological data, injury mechanisms and current prevention strategies. Unfortunately, there is only limited scientific work published on the specific disciplines of freestyle skiing, hence most information has been inferred from other disciplines.

Chapter 2: Skiing Injuries and risk factors

2.1 Epidemiology

This chapter will focus on skiing related injuries, particularly to the anterior cruciate ligament (ACL), including the epidemiology, known risk factors and existing programs and ideas about injury prevention. This information is the basis to implement efficient injury prevention strategies which is the goal of the current project.

The first studies on snow sport injuries were conducted in the early to mid 1940's in the USA (Moritz, 1943). Following this, other epidemiological studies succeeded and demonstrated that skiing is a sport with a significant injury risk (Earle, Moritz, Saviers, & Ball, 1962; Tapper, 1978). In the last forty years, overall injury rates have decreased from approximately 5 to 8 injuries per 1000 skier-days¹ to about 2 to 3 injuries per 1000 skierdays (Koehle et al., 2002). An underestimation of the real injury rate is assumed due to an unknown number of unreported cases. However, injury patterns also changed within the same period of time. While upper extremity injuries remained constant over the last three to four decades, the number of lower leg injuries reduced by approximately 53% (Hunter, 1999). Moreover, lower leg fractures decreased by approximately 87% and severe ankle injuries have shown a reduction of 92%. However, the rate of severe knee injuries involving a rupture or tear of one or more ligaments has tripled since 1980 (Campbell, 2008; Johnson, Ettlinger, & Shealy, 2005; Maes et al., 2002). New binding systems with multimodal release mechanisms as well as higher and stiffer ski boots that embed the ankle were developed in the late 1960's. It is assumed that the improved equipment of the last decades that protect the ankle and tibia are now contributing to the increase in knee injuries (Figure 8).





Figure 8: Development of injuries in alpine skiing [modified from Senner (2002)].

Due to changes in ski boot design the forces acting at the shoe are redistributed to the knee (Figueras, Llobet, Buló, Morgenstern, & Merino, 1985; Hauser & Schaff, 1987; Johnson, 1995). In the USA between 80 000 and 100 000 ACL injuries are reported every year and worldwide about 70,000 skiing related ACL injuries. This leads to estimated costs of approximately one billion dollars for repair and rehabilitation. This means that it costs approximately 15 000 USD per injury not including medical costs associated with future complications that are likely to occur following ACL-reconstruction (Griffin et al., 2000). Adriane and colleagues (2002) reported that in the last four decades one fourth of all skiing injuries involved trauma of the knee. According to Hunter (1999) this percentage ranges from 20% to 36%. In a 22-year study of skiing injuries, the amount of serious knee injuries are the only injuries that have been significantly increasing from 1960 (Ettlinger, Johnson, & Shealy, 1995). This may be attributed to higher speeds, incorrect adjustments of bindings, evolution of techniques and equipment such as plastic shoes with thicker soles and higher shafts (Adriane et al., 2002). The same authors reported ten years later about 2 430 full ACL ruptures out of a total of 17 967 injuries over 6 400 000 skier visits. They emphasized that ACL tears became the most common serious injury in alpine skiers. According to the authors, the incidence of serious ACL injuries increased by 231%, whereas lower leg injuries decreased by 83% within the observation period. These findings and possible reasons for this development (chapter 2.1.1) are in accordance with the study of Adriane (2002). However, at the International Society for Skiing Safety Congress in May 2003 it was noted that in the previous three years the rate of serious knee injuries was starting to reduce, which was presumably attributed to the shorter carving skis that were introduced in the mid 1990's (chapter 1.2.2.1) potentially leading to decreased torques (NSAA, 2008).

Epidemiological data on mogul skiing is only available for competitions. According to Heir (2002) 45% of all injuries in World Cup freestyle skiing are knee injuries and one fourth of the participants in the FIS Freestyle World Championships 2001 in Whistler/Blackcomb, Canada previously suffered one or more ACL ruptures. In an observational study using video analysis in World Cup freestyle mogul skiing, Heir (2007) observed that the majority of ACL injuries occurred when the skier was out of balance with the weight on the injured leg. This high incidence of knee injuries is in accordance with the findings reported by Fuller (2006) who is the initiator of the FIS Injury Surveillance System (ISS) at the Oslo Sports Trauma Research Centre. Information on all injuries from official training and competitions in World Cup events and World Ski Championships have been collated to provide an overview of the overall injury distribution to World Cup athletes (Oslo Sports Trauma Research Center, 2006). One third of the 151 high-level freestyle skiers interviewed suffered injuries in the season of 2006/2007. These were categorised in several body parts and a fourth of the indicated injuries involved the knee, which is a higher percentage than for all other injury sites.

Inoue (2006) previously conducted a study on the Japanese national mogul ski team over a ten-year period and found that there is a high risk of ACL injury on the landing after jumps. Eleven participants (18% of the males and 29% of the females) sustained ACL injuries immediately following a jump manoeuvre with no obvious mechanism. In 1982, Dowling (1982) found that more than half of the injuries in competitions in US ski resorts occurred after jumps. This study detected a relatively low incidence of injuries with 2.8 injuries per 1000 skier days in the period between 1976 and 1980. The low incidence of injuries might reflect the fact that U.S ski areas banned inverted aerials just before this study was conducted - according to the advice from legal experts following several cases of skiers suing for damages of up to \$ 1.5 million (Fry, 2007). However, this ban has since been overturned. A more recent article examined the injuries of mogul skiing in China including the characteristics and main reasons for these injuries (Ying, Yuhua, & Mei, 2008). Unfortunately, the full paper is only available in Chinese.

2.1.1 Specific Ski Injuries

Skiers are rather susceptible to lower limb injuries (Hagel, Goulet, Platt, & Pless, 2004). However, injuries specific to skiing include the upper extremities, the lower extremities, the head and the spine. A very common ski injury of the upper extremities is a rupture of the ulnar collateral ligament, also known as the 'skier's thumb'. A fall during skiing is the most likely cause of any damage to the ulnar collateral ligament (Hunter, 1999). This injury comprises 8% to 10% of all ski injuries (Figure 9) and commonly results from a fall on the hand with the ski pole maintained in the palm stressing the metacarpophalangeal joint. A full rupture is often easily treated by surgery and the patient can usually return to skiing and work within one to two days.





Since 1972, shoulder trauma represents 4% to 11% of all ski injuries (Figure 9) and 22% to 41% of upper extremity injuries including rotator cuff tears or strains, acromioclavicular separations, clavicle fractures and anterior glenohumeral dislocations (Kocher, Dupree, & Feagin Jr, 1998; Kocher & Feagin Jr, 1996; Langran, 2008). The most common mechanism for these injuries is a fall on an extended arm or an abduction-external rotation torque due to the ski pole pulling the arm while the skier overtakes the arm, namely 'pole planting'. Other shoulder injury mechanisms include collisions with trees or other skiers. There is a prevailing high risk of recurrence in the population under

the age of 25 years and a common treatment is an arthroscopic stabilisation. However, people over the age of 40 get conservative treatment with an arm sling and physiotherapy as their likelihood of recurrence is significantly lower (Hunter, 1999).

Head injuries compose approximately 10% to 20% of all ski injuries (Langran, 2008). The majority of these cases (approximately 90%) are minor injuries such as cuts or contusions and 10% are potentially serious head injuries including skull fractures, hematomas and swelling around the brain as well as open head wounds. There are three commonly known head injury mechanisms: 1. collisions with another person or an object; 2. impacts with snow surfaces which are most common amongst beginners who lose their balance catching an edge; 3. lift accidents which are a common scenario as the T-bar is still recoiling when it goes around the turn wheel and hits the head on its way back. It is beyond the scope of this thesis to go into the precise medical details of the treatment of these.

The percentage of spinal injuries in skiing is comparably low at 0.1% (Figure 9). However, these injuries can have particularly devastating consequences for the skier with a potential loss of sensation and function distal to the lesion which could cause paralysis. Spinal injuries most commonly occur in conjunction with falls from more than ten feet and manifest themselves in either a flexion/ hyper-extension where the head flexes and then rapidly extends (at the neck), or compression injuries, where the bones are compressed (Langran, 2008). An appropriate treatment depends on the individual condition and the affected part of the spine.

Life-threatening injuries in skiing are rare. According to Tough and associates (1993) the death rate is 1 to 1.3 per 1 million skier days. In the American season 2006/2007 this rate was 1 per 2.5 million skier days (NSAA, 2008) which amounts to 22 deaths. This rate has been steadily decreasing since the 2001/2002 season (Langran, 2008). A Canadian study reported that a 31-year-old experienced male skier is the individual that is most likely to suffer a deadly accident by losing control and colliding with an object or another skier during downhill skiing.

These researchers stated that the fatality rate in skiing was 1 tenth of that compared to water sports (Tough et al., 1993). In swimming, 62.1 fatalities per million participants occurred in 2006, in cycling it is 23.2 per million participants in 2005 whereas in skiing it is 2.07 fatalities per million participants (2006/ 2007) (NSAA, 2008). Hence, alpine skiing is not associated with life threatening accidents. Interestingly, the ratio of skiing to

snowboarding death rates amounts 1.54 to 1 and contrary to popular belief skiers are more likely to collide with fellow skiers than snowboarders. (Shealy, Johnson, & Ettlinger, 2006).

The following sub-section will address this and identify skiing specific injuries and their prevention strategies.

2.1.2 The Anterior Cruciate Ligament in Skiing

The cruciate ligaments are situated in the middle of the knee joint and are of considerable strength to provide stability and proper alignment of the load bearing surfaces (Johnson, Shealy, & Ettlinger, 2007). They are named 'anterior' and 'posterior' cruciate ligament reflecting the position of their attachment to the tibia where they are crossing each other. The ACL is attached in the front of the intercondyloid eminence of the tibia, being blended with the anterior aspect of the lateral meniscus.



Figure 10: Left knee joint from behind, showing interior ligaments (Gray, 2000).

It connects from a posterio-lateral part of the femur to an anterior-medial part of the tibia which prevents anterior translation of the tibia (Figure 10). The ACL also prevents internal and external tibial rotation and provides resistance against adduction and abduction movements (Gollehon, Torzilli, & Warren, 1987; Piziali, Rastegar, Nagel, & Schurman, 1980). According to Butler (1980) the ACL contributes about 85% of the ligamentous stability of the knee joint in an flexion of 30°. A loss of the ACL may lead to ainstability of the knee joint for varus-valgus loads in joint flexion between 20° and 40° (Girgis, Marshall, & Monajem, 1975; Torzilli, Deng, & Warren, 1994). The range of motion

internal rotation is noticeably smaller than for external rotation. At low forces applied by the quadriceps muscles as antagonists to the ACL, the knee joint is considered instable and a pure internal rotation at hyper-flexion is critical (Lehner, 2007). Axial impulsive loading of the knee joint combined with a valgus knee moment is most likely to cause a serious ACL injury. This is often combined with internal or external rotation with a single leg landing and an extended knee (Boden, Dean, Feagin Jr, & Garrett Jr, 2000; Fleming et al., 2001; Krosshaug & Bahr, 2005; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Teitz, 2001).

Cadaver experiments showed that yielding of the tibia in bending can occur at an applied moment of 126 to 191 Nm (Cezayirlioglu & Bahniuk, 1982) and fracture in bending can occur at moments of 300 Nm (Asang, 1976). It was suggested that the ligaments at the knee are more prone to injury than the tibia (Piziali, Nagel, Koogle, & Whalen, 1982). The range of failure loads for the ACL has been reported to be between 1200 and 2500 N using cadaver specimens (Hollis, Lyon, & Marin, 1988; Woo, Hollis, Adams, Lyon, & Takai, 1991). Even though these cadaver tests were performed at 30° of knee flexion the susceptibility to ACL injuries are also determined by, gender and alignment of the tibia relative to the femur. In previous investigations, an isolated valgus knee moment (26 Nm) showed no significant effect on ACL strain under a fixed knee flexion angle (0, 15, 30 degrees), but the combination of valgus moment (26 Nm) and anterior force (106 N) exposed the ACL to a significantly higher strain (Withrow, Huston, Wojtys, & Ashton-Miller, 2006). Berns (1992) and Duerselen (1995) suggested that an external tibia rotation in conjunction with a valgus alignment of the lower extremity exposes the ACL to extreme stress through the entire flexion range of the knee. Depending on the sporting activity female athletes are up to eight times more prone to ACL injuries than males due to possible differences in ACL size, notch size and shape, hormonal differences (e.g. menstrual period), inherited skills and coordination and neuromuscular activation patterns (Ireland, 1999). Even though it is well known that muscle size reduces and tissue generally alters during the aging process, no studies have shown a correlation between age and the susceptibility to ACL injuries. However, increased age decreases the chance of a re-tear after ACL reconstruction, which is presumably attributed to moderate reduced exposure to high impacts (Brockenbrought, 2008).

The ACL has been shown to be particularly susceptible to injury while skiing and the ACL injuries are often associated with injuries to other structures within the knee (Hame,

Oakes, & Markolf, 2002; Hunter, 1999; Johnson et al., 2005; Koehle et al., 2002). Griffin et al. (2000) distinguish four categories for risk factors for non-contact ACL injuries; specifically environmental, anatomical, hormonal and biomechanical factors. Consequently, investigations are warranted to establish prevention programs related to these categories.

Injuries of the ACL are divided into three different grades which can involve extreme stretching or tearing of the ligament. A grade 1 ACL injury means no laxity ('give') in the ligament when put under strain. In that case few or no ligament fibres are torn. Grade 2 injuries indicate some laxity in the ligament, but with a definite endpoint, meaning some but not all ligament fibres are torn. For a grade 3 ACL injury the knee exhibits a complete give in the ligament which indicates a full rupture with all ligaments ruptured (Gray, 2000).

More than 90% of all accidents in skiing are caused by a fall not induced by other skiers. Hence falling is clearly the most common reasons for injury (Burtscher, Puhringer, Werner, Sommersacher, & Nachbauer, 2009). Discussions on the injury mechanisms are, in general, controversial. According to Hame (2002) investigations of injury mechanisms are required. Injury mechanisms of the ACL during knee hyperflexion have not been investigated in alpine skiing to date. Also, the correlation between knee joint loading and the associated moments resulting from various movements and loads, such as internal and external tibial rotation or varus-valgus loading, have not been investigated in depth (Lehner, 2007). Despite this, detailed investigations of the parameters contributing to injuries are vital so to fully understand injury mechanisms and therefore enable the implementation of appropriate preventive strategies (Fleming & Beynnon, 2004).

ACL injury mechanisms in elite alpine competitors are different to those of recreational skiers in that knees are deeply flexed in a seated body position, with the feet accelerating forward relative to the upper body (Johnson, 1995). The ACL injury mechanisms in skiing are reportedly different to those in other sports, where deceleration, change of direction or direct-blow injuries, in conjunction with strong compression, commonly occur (Hunter, 1999). However, it is obvious that loading patterns and injury mechanisms in normal alpine skiing are again different to those of freestyle skiing where injuries commonly occur in conjunction with strong compression (Heir et al., 2007; Inoue et al., 2006)
Recently, surgical techniques have become more sophisticated and less invasive and traumatic. Unfortunately, although treatment strategies have improved, injury prevention strategies have remained unchanged and have not been investigated (Hunter, 1999). The latter is required whereby researchers are investigating the different performance parameters and typical injury patterns in the various disciplines of snow sports. The current thesis is motivated by the large incidence of severe knee injuries and will contribute to innovative injury prevention strategies with regards to equipment improvement. The following sections will provide an introduction to the risk factors knee joint injury in alpine skiing.

2.2 Risk factors for knee injuries in skiing

Generally age, sex, skill level, equipment, ski school attendance, helmet wearing, alcohol and fatigue are common risk factors for injury in skiing (Sulheim, Ekeland, & Bahr, 2005) as well as other factors discussed in chapter 2.3. Meeuwisse and colleagues (2007) developed a dynamic, recursive model of etiology in sport injuries. According to the model an injury can occur due to repeated participation in sporting activities. Either the participant will increase their muscle strength required for the sport or they will be a higher risk of injury (Figure 11). The model classifies the factors that affect the risk of injury in sporting participants. They are as follows:

- Intrinsic risk factors
- Extrinsic risk factors
- Inciting events

Injuries specific to the ACL in skiing occur by both passive (extrinsically) and active (intrinsically) forces. The proportion of these forces to the ACL is variable (McConkey, 1986).





2.2.1 Intrinsic risk factors

Intrinsic risk factors are predisposed factors that are specific to the individual such as fitness, previous injury history or anatomy. Several studies suggested methods of evaluating the risk factors for injuries between genders (Hagel et al., 2004; Hunter, 1999; Koehle et al., 2002). Floerenes and associates (2009) concluded that in world cup skiing the technical demands, high speed and high forces seemed to counteract factors related to gender. Despite this, in the common skier, Ekeland et al. (2005a) reported that in 12 Norwegian ski resorts, over a period of two years, the percentage of knee injuries to be almost double for female than male skiers. Johnson et al. (2005), as a result of a long term study, stated that the likelihood of ACL injury is 2.4 times higher for females; a trend that is supported by other studies (Hagel et al., 2004; Koehle et al., 2002; Roos, Adalberth, Dahlberg, & Lohmander, 1995).

Controversial reports are found in the literature regarding the influence of age and the susceptibility to injury. One study revealed that injury severity increases with increasing age as a greater number of adults require treatment for their injuries than children (Ekeland, Rodven, & Hansens, 2005b). However, children have a three-fold risk of head injuries than adults (Sulheim et al., 2005) and according to Hagel et al. (2004) young people between 12 and 17 years have the highest risk of injury, including knee injuries.

Regardless, from a medical point of view, adults older than 26 years seem to be more prone to knee ligament injuries. This is due to the ligamentous tissue changing and becoming less resilient. With increasing age connective tissue cells become less responsive to growth factors. (Howard & Anastassiades, 1993; Roos et al., 1995). Another contributing risk factor is the level of experience as beginners are more often injured than more experienced skiers (Langran & Selvaraj, 2004).

2.2.1.1 Stabilisation of the knee joint

Stabilisation of the knee joint is crucial to avoid injuries and is strongly dependent on anatomical factors. The knee joint transfers weight from the femur to the tibia. Due to its complexity the requirements with respect to stability and mobility are higher (Martini et al., 2001). Injuries occur when the load or movement induced exceeds the capacity of anatomical structures. Stabilisation is achieved by passive (e.g. ligaments) and active structures (e.g. embracing muscles) and stabilise the knee in six directions (flexion/extension, varus/valgus, external/internal rotation). The relationship between these stabilisation components are displayed in Figure 12. In addition, if a ligament or a muscle is injured and thus vulnerable, it poses another intrinsic risk factor and impairs the joint stability. Loading of the knee joint depends on both, internal factors such as alignment between femur and tibia and external factors is modified by a compensating mechanism the load can partly exceed the tolerance level and this can lead to an overloading of the ligaments (Palastanga, Field, & Soames, 2006).



Figure 12: Relationship between stabilisation components of the knee (Feagin Jr et al., 1987).

2.2.1.2 Muscle activation patterns

The activation of the muscles surrounding the knee are important for avoiding ligament injuries within the knee. Muscle imbalance between quadriceps and hamstrings has an

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effect on the risk of ACL injury (Barrone, Senner, Schaff, & Rosemeyer, 1996; Grace, Sweetser, Nelson, Ydens, & Skipper, 1984). If the quadriceps muscle has too little or too much power to keep the tibia and the femur aligned the ACL must withstand the excess load. Thus, if the muscles are fatigued, not properly prepared or the neuromuscular control of the hip or the knee is impaired the ACL may be at risk for rupture (Myer, Ford, Palumbo, & Hewett, 2005). Figueras et al. (1987) investigated the activation of the quadriceps and hamstring muscles and simulated knee forces when the skier loses their balance backwards. The mathematical model was based on 23 instances of ACL injury and validated this model using EMG measurements. Results indicate that a failure of the hamstrings against the contraction of the quadriceps during the effort to regain control in a backward fall situation in skiing can cause an ACL rupture by the forward displacement of the tibia. This is referred to by McConkey (1986) as the quadriceps-induced concept of injury, which often occurs in combination with passive forces.

2.2.2 Extrinsic risk factors

Extrinsic risk factors are may affect the risk of injury. These are from the environment and include safety equipment, terrain and other skiers. Social behaviour and the slope surface can also have an influence on skiing injuries (H. Boehm & Senner, 2007; Finch & Kelsall, 1998). Hence, there is a correlation between snow quality and risk of injury. Overgrooming of the slope or skiing from powder onto ice, for instance, can increase the skier's speed and thus be hazardous (Penniman, 1999). Obstacles on the slope such as trees, rocks or moguls can be considered risk factors. Natural moguls appear as a consequence of ski turns and increase in numbers as the day progresses posing a potential risk as they require particular attention and generate fatigue of quadriceps.

The development of binding systems and ski boot technology has been of focus in the last three to four decades but despite this injury patterns have changed within the same time (Hunter, 1999; Natri, Beynnon, Ettlinger, Johnson, & Shealy, 1999). More in depth reviewing of ski boots and bindings as well as other intrinsic and extrinsic risk factors will be covered within the next sub chapters.

2.2.3 Inciting events

As mentioned previously, ruptures of the ligaments are the most common ski injuries to the knee. Generally three different mechanisms of ACL injuries in normal alpine skiing have been proposed. The first is the combined valgus and external rotation (Figure 13,a), which occurs when the skier is falling forward between the skis after catching an inside edge. The primarily injured ligament in this injury mechanism is the medial collateral ligament (MCL), however in 20% of the cases the ACL is also torn (Koehle et al., 2002; Natri et al., 1999).

The second mechanism is the boot-induced anterior drawer (BIAD), which means the boot is forcing the tibia anteriorly when landing on the back of the ski with an almost extended knee (Figure 13,b). An international panel of various experts regarding knee injuries and specific ski injuries proposed the BIAD mechanism was the most frequently encountered injury mechanism during mogul skiing competition (Heir et al., 2007). However, these results are based on observational data and appropriate studies including both qualitative and the quantitative mechanical analysis of freestyle mogul skiing movements have not been investigated. This mechanism commonly occurs following jumps when the athlete is landing off-balance with the tail first or in mogul skiing when the skier hits the moguls in an uncontrolled 'back seat' manner (Natri et al., 1999). In that context the term "Big bump, flat landing" has been established by Johnson and associates (1974).

The third mechanism is the phantom-foot phenomenon (Figure 13,c). It describes a fall backwards between the skis, catching the inside edge of the downhill ski leading to a forced internal rotation of the leg. This rotation can also be described as anterior tibial translation which induces shear forces on the knee (Benoit, Lamontagne, Greaves, Liti, & Cerulli, 2005).



Figure 13: Common mechanisms of anterior cruciate ligament injury: a.) valgus external rotation; b.) boot induced anterior drawer; c.) phantom foot mechanism (Koehle et al., 2002).

The BIAD mechanism and the phantom-foot are the most commonly known causes of ACL injury. Dangerous situations potentially leading to a phantom foot ACL injury are associated with the attempt to get up while still moving after a fall, the attempt to recover from an off-balance position and the attempt to sit down after losing control (Johnson et al., 2007). Isolated ACL ruptures following a BIAD mechanism are often the result of a combination of previously described forces (Figure 14). There are general recommendations on the appropriate response to this potentially dangerous situation (chapter 2.3.7).



Figure 14: Isolated ACL rupture proposed injury mechanism (adopted from (McConkey, 1986)).

The next paragraph will name a few general aspects and existing strategies on how to prevent the risk of accident and injury during skiing.

2.3 Injury prevention strategies

To date, several publications have been released detailing injury prevention strategies which have been divided into individual tactics and community or industrial scales. However, no injury prevention strategies exist specifically for freestyle skiing. There is also a trend to incorporate challenging movements and tricks such as 'inverted aerials', 'rail slides' and 'fakie' landings after jumps (see glossary). These new manoeuvres leave participants vulnerable to injuries that may be otherwise avoidable with a greater understanding of biomechanical parameters applicable for equipment design, technique instructions or jump constructions. Hence, research into injury prevention in freestyle skiing has increased with the popularity of the sport and remains under-investigated. The techniques and movements in traditional alpine and mogul skiing as a specific freestyle discipline are unlike. Mogul skiers show mainly eccentric muscle activation, a larger range of hip and knee movement, shorter movement cycles and larger hip and knee angular velocities than traditional alpine racers (Krosshaug et al., 2002). Apart from the two compulsory jumps, mogul skiers experience high levels of impact as they are partly off the snow between the moguls yielding repetitive landings

As normal alpine skiing and mogul skiing also differ in injury and presumably loading patterns more preventive research is required. The following sub-section will introduce programs and ideas about injury prevention from the current literature. In general, injury prevention strategies are numerous, but only few are related to skiing and none have been validated for freestyle skiing. This underlines the need for current research.

2.3.1 General aspects of Injury prevention

Several inherent risks in snow sports regarding safety should be considered with personal responsibility being the key factor. Skiers going off-piste for instance should never ski alone and should always be aware of the presence of a potential avalanche. Sherker and colleagues (2005) also encouraged the consideration of alcohol, fatigue and drug misuse as a major contributor to snow sport related injuries. Safety cannot entirely be ensured on ski slopes but the best general advice to minimize injury risk is to follow the FIS code of conduct. Advice should be given to everyone on the slope to 'expect the unexpected' and 'ski anticipatorily' (Langran, 2008). General recommendations for injury prevention in alpine skiing are given. Those are, for instance, the execution of general conditioning programs, choice of equipment appropriate for the skier's skills, professional adjustments, speed control and termination of skiing before becoming fatigued (Hunter, 1999). The next sub-chapters will discuss the existing protective gear and strategies that should aid to preventing serious injuries while skiing.

2.3.2 Helmets

The use of ski helmets and its efficiency with regard to injury avoidance is in debate within the media and the snowsport research community. It should to be noted that on the basis of results to date, there is no clear evidence that helmets are effective in reducing fatalities in alpine sports (Shealy et al., 2006). According to Senner and associates (2009), however, their computer simulation typical collisions compared to damage thresholds has demonstrated that ski helmets can effectively protect the head from injuries such as

concussion. It is important to be aware that helmets, do not protect skiers and snowboarders against high speed impacts (Langran, 2008).

2.3.3 Ski Boot Design

The ski boot design as an extrinsic risk factor has a particular influence on injury patterns in skiing. Several studies investigated different ski boot features, but few in conjunction with freestyle skiing (Corazza & Cobelli, 2005; Hauser & Schaff, 1987; Kryszohn, Lehner, & Senner, 2005; Petrone & Marcolin, 2007; Schaff & Hauser, 1985, 1989, 1993; Schaff, Hauser, Schattner, & Kulot, 1987; Schaff, Schattner, & Hauser, 1987; Schaff, Schattner, Kulot, & Hauser, 1989; Senner & Schaff, 1995; Walkhoff & Bauman, 1987). Common ski boots force mogul skiers into an unnatural posture with a distinctive backward lean because the necessary flexibility of the ankle joint for absorbing bumps is restricted. Thus, the natural damping capacity is confined as lowering the buttock in a backward leaning position as opposed to the lowering of the centre of mass above the centre of the ski. The greater the range of knee movement, the greater the backward lean (Ofner, 2006). The retropatellar pressure is supposed to be increased, potentially leading to ligament damage and cartilage degeneration. Therefore, freestyle skiers are particularly exposed to potentially harmful movement restrictions due to relatively stiff ski boot shafts. German orthopaedists and scientists recommend modifications in ski boot design to potentially reduce knee ligament stress (Schaff & Olbert, 1996). As long as scientific evidence for the effectiveness of specifically modified ski boots is lacking, no reliable recommendations, in terms of a ski boot model for freestyle skiing, can be made with regards to injury prevention.

A recent study by Boehm and Senner (2007) tested ski boot characteristics such as canting settings and the "V-position", which describes different adjustments of the ski boot with respect to the natural foot position. Constraints of ski boots led to a clinically significant valgus mal-alignment with an increased risk of ACL injuries. For landing, a neutral limb alignment without these potentially harmful constraints could reduce the risk of ACL ruptures (Chaudhari & Andriacchi, 2006). Therefore, the appropriate adjustability is a desirable ski boot feature for freestyle skiing in terms of injury prevention.

Schaff & Olbert (1996) examined the loading of the foot sole during mogul skiing with respect to the ski boot design. The investigators assumed that the use of a ski boot model with a significantly greater forward lean compared to normal ski boots would act as a

potentially injury prevention method. However, they specifically recommended further investigations with advanced 3D video analyses and reliable kinetic measurements to gain knowledge about tissue loading in mogul skiing with specific equipment (Schaff & Olbert, 1996) (chapter 3.2.2).

Corazza & Cobelli (2005) suggested an innovative ski boot to increase the intrinsic knee stability to a more appropriate adjustment of the lateral stance. This ski boot was novel in that the orientation of the leg with respect to the ground. The 'Stance Geometry System' (SGS) allowed for adjustment of the posture in the frontal plane by rotating the sole of the boot about the anterio-posterior axis.

There are controversial opinions about the stiffness of ski boots. The stiffness of a ski boot is defined by the force needed to move the shaft forward by about 1 degree as illustrated in Figure 16 (Bürkner & Simmen, 2008). A common belief is that the ski boot stiffness needs to be greater for more advanced skiers. Thus, the more dynamic or aggressive the style the stiffer the boot needs to be. However, a dorsally shifted position of the CoM with stiff ski boots has been observed, which carries the risk of a backward fall and thereby enhances the likelihood of an ACL rupture (Schaff & Hauser, 1989, 1990a, 1990b). It has been suggested that a softer ski boot can reduce the transmitted tension and thus contribute to e.g. a decreased risk of tibial fractures (Bürkner & Simmen, 2008).

Schaff & Hauser (1993) introduced the concept of an opening rear spoiler that 'releases with a certain force application. It was concluded that ligament loads as well as peak forces were lower in a soft setting and the movement could be decelerated progressively. However, this concept aimed at a reduction of the damage during the inciting event and is therefore an injury prevention strategy in that it is trying to reduce the consequences of the backward fall, is not trying to avoid the backward fall commonly caused by a movement restriction (Friedl, 2007).

Noe et al. (2009) observed that gastrocnemius medialis and vastus medialis muscle activity decreases when wearing ski boots. A stiff ski boot even reinforces this effect as supported by Machens (2006). Taking into account that both ligaments and muscles stabilize the knee joint, this would support the demand for a flexible ski boot (Friedl, 2007; Machens, 2006; Olbert, Schaff, & Schumacher, 1994; Schaff & Hauser, 1990b).

Figure 15 displays the angle and torque that define the boot stiffness. The angle α defines the range of the anterior motion from the upright zero position and the M_y indicates the amount of torque needed to bend the ski boot (Hauser & Schaff, 1987).



Figure 15: Illustration of the angle α and the torque My that define the boot stiffness (Hauser & Schaff, 1987).

To protect the ankle joint the ski boot's flexibility in anterior direction must not exceed a bending angle of 35°. According to Hauser & Schaff (1987) a ski boot that is too stiff can lead to insufficient range of motion at the ankle joint in an anterior direction, as previously described, so that a posture with only the knees and the hips bent can be attained leading to a loss of control.

2.3.4 Bindings

Binding adjustments and maintenance have been cited as a possible preventative measure for skiing related injuries (Finch & Kelsall, 1998; Koehle et al., 2002). Kelsall's (1999) findings revealed that properly adjusted ski bindings have the potential for a 3.5-fold reduction in lower extremity injuries, particularly knee injuries. Furthermore, Kelsall suggests meticulously adjusted bindings as a prevention strategy. In 2001 the ski binding international standards were modified. A rising number of injuries and a steadily growing ski community led to an improvement of the ISO norm 11088 for binding adjustments (Laporte, Binet, & Bally, 2003). However, ski bindings, in general, continue to have a great potential for improvement. A detailed analysis of injury mechanisms in skiing is a prerequisite for the optimisation of ski binding systems as well as ski boots.

A new binding system was developed by Intelligent Binding Systems (IBS) in order to meet the current requirements and to parallel the developments in ski materials, techniques and execution of skiing performance. The 'Revolution X' binding had an innovative three dimensional release system, specifically including lateral, medial, anterior, posterior and longitudinal directions (Ruede, 2005). The release feature in the posterior direction was implemented to prevent potential ACL injuries caused by common injury mechanisms (chapter 2.2.3). The idea of bindings with more than two release modes was supported by Natri and colleagues (1999). This ski binding innovation, however, is not currently produced due to a lack of demand.

A 'so-called' knee friendly ski binding was developed in 2008 with a lateral heel release in order to reduce the risk of ACL injuries. This innovation has an off-centre pivot point and only releases inwards in order to avoid harmful known injury mechanisms as described in chapter 2.2.3. This innovation was invented by Rick Howell in Vermont and was nominated for the annual innovation awards for the 2008/ 2009 season (E. Buchanan, 2008).

Many knee injuries occur with the binding not releasing. A reason for this problem is that with current bindings the load that can induce an injury to the hyperflexed knee is smaller than the load encountered for normal skiing manoeuvres (Natri et al., 1999).

2.3.5 Equipment maintenance

It is crucial to check equipment regularly or to give it to a reputable shop or company that is able to do it appropriately. Potential hazards originating from wrongly fitting equipment such as skis that are too long making turning more difficult or bindings that are set too high for the individuals skill level and are therefore likely to cause injury. Ski boots should fit properly and skiers should generally not be discouraged to use a hiring shop's services and knowledge in order to make the equipment fit optimally. Bindings should be serviced at least once a year pending on the frequency and amount of skiing days, because they require cleaning, lubrication and re-setting. A daily performed self-test on the bindings are recommended by the Society for Skiing Safety to ensure that the binding is set correctly for individuals needs. A self-test is performed by twisting the boot inwards while the ski is angled so that the front inside edge is on the ground so that the binding will release at the front piece. The other way is to slide the foot back with the ski flat on the ground until the leg is extended and the heel can be lifted out of the back piece of the binding.

2.3.6 Conditioning

Pre-season conditioning training is a common method to prepare the body for the demands of snow sport. As oxygen supply at higher altitudes reduces, the human body needs to acclimatise and initially tends to fatigue sooner compared to physical activities on sea level (De Marees, 1996; Saibene, Cortili, Gavazzi, & Magistri, 1985). Pre-season training is recommended by the Canadian Academy of Sports medicine as a useful injury prevention strategy in snow sports in order to prevent overloading the human body beyond the individuals physical capability (Bridges & White, 2006).

Recently published intervention programs have aimed to reduce the risk of ACL injuries through neuromuscular system training: plyometrics, strength training, stretching, balance and correct technique (Grindstaff, Hammill, Tuzson, & Hertel, 2006). These neuromuscular training programs demonstrate the potential to reduce associated risk factors for injuries as well as injury rates in both individual and team sports (Heidt Jr, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005; Myer, Ford, McLean, & Hewett, 2006; Myer et al., 2005).

Grindstaff (2006) emphasizes that a sport-specific neuromuscular training program consisting of plyometrics, balance and agility exercises should be undertaken for the prevention of non-contact ACL injuries and to improve physical fitness.

The possibility that resistance training might also enhance the functional capability of noncontractile tissues such as ligaments with regards to stabilisation of the knee joint seems to be underestimated. Morrissey (2010) recommends resistance training to the knee extensors with the knee near full extension for stiffening the knee as a protective measure.

It is generally advisable to warm up and cool down before and after skiing. Also fatigue is often under-estimated and should be recognised. Many injuries occur after lunch, and towards the end of a skiing holiday when fatigue occurs more quickly.

2.3.7 Instructions and awareness

The appropriate verbal feedback from highly qualified coaches and instructors as an educational component is also a large contributor to the success of injury prevention.

Vermont Ski Safety developed ACL awareness training. It is a DVD based video training and skier education program for both the general public and professionals such as staff, physical therapists, doctors, schools, orthopaedic outpatient facilities and retail facilities. The program involves sensitizing people for potentially dangerous every-day situations and body postures so that people can try to avoid them before they occur (Johnson et al., 2007). Participants were given guidelines to reduce the risk of injury while falling. The authors of this study demonstrated that the program successfully prevented ACL injuries.

Events leading to ACL injury are subtle and in general give the skier little or no warning of impending injury. In alpine skiing there is no conclusive evidence to show that traditional ski instruction reduces injury frequency (Koehle et al., 2002). However, there are recommendations in terms of avoidance of high risk ACL behaviour, such as

- Do not fully straighten your legs when you fall. Keep your knees flexed.
- Do not try to get up until you have stopped sliding.
- Do not land on your hand. Keep your arms up and forward.
- Do not jump unless you know where and how to land. Land on both skis.
- Keep hips above knees
- Keep arms forward
- Keep feet together
- Keep hands over skis (Johnson et al., 2007)

2.3.8 Resort designs and regulations

The so-called 'New School' movements leave skiers vulnerable to intrinsic injuries due to a level of difficulty insufficient for the skiers skill level, on the one hand. On the other hand the resorts' special freestyle features such as purpose-built jump constructions or mogul slopes need to be designed to meet safety criteria that can be gained through scientific investigations. A jump construction, for example, includes the correct arrangement of the inclination of in-run, steepness of transition and appropriate length of table tops. Landing zones as well as mogul slopes should be available in various degrees of difficulty and need to be marked appropriately.

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There are several ideas within the current literature regarding resort designs and regulations and the possible effects on injury exposure. Biner's (2003) flow-zone concept aims to implement ungroomed parts on, or between existing slopes in order to offer a variety of challenges of variable difficulty that will potentially motivate skiers to experiment with different techniques. Most existing mogul slopes are on steep slopes that are not accessible to snow cats for grooming and are therefore avoided by most skiers due to their inherent challenge. Hence, in the flow-zones, skiers of every skill level and age group can practice mogul skiing at low speeds in a safeguarded environment. This concept can be considered a contribution to the safety of ski fields, because it can potentially enhance the skiers' skills and reduce the number of high speed accidents as the velocity in these kind of mogul slopes is significantly lower than on groomed slopes of similar inclination (Brandauer et al., 2009).

A certification system, as in martial arts and Scuba diving, could be incorporated whereby individuals would accumulate skills and achieve certain categories such as 'level two freestyle skier'. In this way, individuals that tend to risk taking behaviour would be encouraged to initially participate in these activities in a safer environment (Koehle et al., 2002).

As mentioned earlier, upside down movements were banned from mogul competitions in 1976 for safety reasons, but reintroduced in the season of 2003/2004 to further promote the sport and its 'new school' trend and emphasize the artistry. FIS is meeting on a regular basis to discuss safety issues and if necessary modify the current regulations. Judges usually make sure that these rules are met by athletes, however, the technique used for competitions often differs from that propagated in the guidelines (Ofner, 2006). This is due to the nature of competitions to aim for the most efficient technique regarding finishing time or athleticism rather than health or injury prevention. This remains a problem that is hard to resolve, thus equipment modifications that alter the motion sequence towards a more healthy performance appears to be desirable.

2.4 Summary

With respect to the current literature, more controlled, laboratory and field based studies, need to be undertaken to determine the causes and preventative methods for the common ACL injury in this discipline. Aspects such as proper technique and instructions, jump

arrangements, specific equipment and of course specific conditioning exercises based on results of appropriate investigations need to be reconsidered.

MacKay and associates (2004) pointed out that there are only few well-designed and controlled studies regarding injury prevention at present. As governments are concerned about physical activity, especially among children and adolescents, there is not enough focus on the risk of injury. Thus, there is a relative lack of evidence of effective preventive measures (MacKay et al., 2004). In the past half century releasable ski bindings were designed to aid in reducing the risk of lower limb fractures and more recently more sophisticated binding developments should unload the knee ligaments (E. Buchanan, 2008). Moreover, the evolution of ski boots contributed to the noticeable reduction of ankle sprains in skiing. However, no product has yet been introduced that can sense and respond appropriately to potentially injurious loads on the knee (Ettlinger et al., 1995). According to Hame (2002) an experimental verification of the discussed injury mechanisms has not been investigated. However, the gathered information lead to the conclusion that detailed investigations of the adequate parameters are crucial to firstly understand existing injury mechanisms and secondly implement strategies for their prevention (Fleming & Beynnon, 2004). A review of existing field testing methodologies will be introduced in the next chapter.

Chapter 3: Biomechanical investigations of skiing technique

This chapter is a review of the biomechanical investigations in the field of snow sport research. There have been three phases of scientific investigations into snow sport activities. The first phase involves qualitative analysis, usually utilised by coaches. In alpine skiing this kind of analysis was first conducted in the early 1930's (Brandenberger, 1934; Reuel, 1930) and included the assessment of forces and resulting motion patterns during skiing (E. Muller & Schwameder, 2003a).

The second phase involves determining the quantitative description of kinetic and kinematic parameters. Some of the most notable early studies of this type in skiing were conducted by Moeser (1957), Fukuoka (1971), Nigg et al. (1977), Kassat (1985), Mueller (1986), Mueller et al. (1991a) and Raschner et al. (2001). More recent investigations were undertaken into the technical aspects of ski instruction (Mueller et al., 1991a) and top ski racing (Raschner et al., 1999; Raschner, Mueller, & Schwameder, 1997).

The third phase is aimed at determining variables that are either important for the optimization of performance or providing information relevant to injury mechanisms. These can be laboratory based, such as Hame et al. (2002) who used cadaver knees to investigate the load on the ACL due to the internal and external rotational torques being applied to the lower leg. They can also be field based such as Schwameder et al. (2000) who measured forces and torques between the ski and the binding when the binding was positioned differently on the ski. Since the third phase is the most relevant to the current project, these publications will be briefly introduced in the following sub chapters. Epidemiological studies of ski injuries were also undertaken while the mentioned three phases have been developing (chapter 2.1).

Methods used in studies to quantify kinematic and kinetic parameters have developed markedly over the years. As advances in technology are made, more possibilities are created to allow for further investigations. One of the first studies required the participants to ski with a mechanical device used to transcribe ground reaction forces to representations on paper strips (Moeser, 1957). Today sophisticated technology is used in skiing biomechanics research such as high speed video cameras and portable force plates. However, due to challenges such as variable temperature, light, surfaces and the tedious process of carrying and setting up the testing equipment, methods of measuring biomechanical parameters are reassessed regularly (Mueller & Bartlett, 1998). Increasingly difficult movements including all anatomical axes being attempted by freestylers make it even more challenging to precisely measure biomechanical parameters. It must be noted that there are several skiing specific congresses being held on a regular basis, such as the International Congress on Science and Skiing (ICSS) and the congress of the International Society for Skiing Safety (ISSS). Of particular importance is the international 'Science and Skiing movement' that was established in 1996 and has released four 'proceeding books' to date (Mueller, Bacharach, Klika, Lindinger, & Schwameder, 2005; Mueller, Lindinger, & Stoeggl, 2009; Mueller, Schwameder, Raschner, Lindinger, & Kornexl, 2001; E. Müller, Schwameder, Kornexl, & Raschner, 1997).

The majority of snow sport studies are only available as congress proceedings or presented papers rather than full articles. The following literature review on biomechanical snow sport research includes information about both the methods of kinematic and kinetic data acquisition for skiing and freestyle skiing.

3.1 Kinematic analysis

Kinematics, describing the motion of objects, has many applications in skiing. These applications range from determining optimal performance parameters to developing specific training equipment for strength conditioning out of season. Both 2D and 3D video imaging are common methods for obtaining kinematic data. Again, little work has been done on the sport of freestyle skiing. Thus, the majority of this review will focus on the primarily investigated areas of alpine skiing, cross country skiing and ski jumping respectively.

3.1.1 Kinematic studies on alpine skiing

The two main goals of kinematic data acquisition are the description of motion characteristics during skiing and the determination of kinematic parameters related to performance (E. Muller & Schwameder, 2003b). A reduced 2D approach has often been used to capture skiing movements due to an easier set up and data processing. For 2D data collection only a single video camera is required which in turn results in a reduced effort for digitization. Most of the 2D analyses focused on the sagittal plane of the skier where the majority of skiing movements are assumed to occur (Federolf, Rauscher, Scheiber, &

Schwameder, 2006; Janura, Cabell, Elfmark, & Vaverka, 2006; Ohgi, Seo, Hirai, & Murakami, 2007; Read & Herzog, 1992; Sasaki, Tsunoda, & Nishizono, 1989; Schaff & Hauser, 1993; Schmolzer & Muller, 2005).

However, Hraski (2009) recently presented a study on body positioning and its influence on the duration of the giant slalom turn using the perspective of the frontal plane. The study divided a group of race competitors into a faster and a slower group and investigated differences in certain body positions such as leg, hip, or shoulder angle for each turn. Federolf and associates (2006) used a single video camera to estimate joint angles and quantify different body postures in order to identify the effects of body position on ski gliding performance. Raschner (1990) was the first person to analyse specific starting techniques in ski racing using a single video camera recording at 100 Hz. He found a regulated single leg jump start to be potentially more efficient than a double leg jump start (Mueller, Brunner, Kornexl, & Raschner, 1991b). Previously conducted studies, using the 2D method in ski jumping, analysed the meaning of the take-off phase for an optimal flight phase (Baumann, 1979; Hochmuth, 1964; Komi, Nelson, & Pulli, 1974). It has been discussed controversially whether certain aspects such as magnitude and direction of release velocity significantly influence the jump distance (E. Muller & Schwameder, 2003a). Another study using a 2D approach in the area of ski jumping focused on the takeoff styles in World Cup competitions recording at 60 Hz also using a single video camera (Sasaki et al., 1989). Janura and colleagues (2006) conducted a long term study on ski jumping showing changes in run-in body positions over a period of ten years. Parameters calculated were the ankle and knee joint angles as well as the trunk segment position, once again using only one camera from a side view. Shealy et al (2008) calculated the flight trajectory on a table top jump using one camera recording at a low frequency of 30 Hz. Attention has been given to the effect of flight positions in ski jumping. Therefore the body postures pre and post take-off have been determined by pinpointing several body parts such as the head, hip, knee, ankle, toe and ski (Ohgi et al., 2007). A more comprehensive 2 D approach on flight style differences was carried out by Schmolzer and Mueller (2005). Eleven cameras were positioned differently to video simultaneously from the same side. This rather comprehensive approach potentially enhances the data accuracy while requiring more efforts.

The major drawback of 2D motion analysis is that off-plane movements cannot be assessed and thus testing results of those movements can be inaccurate. Ski jumping might

be a discipline that shows most of the relevant motion to be investigated only in the sagittal plane and therefore 2D videos are potentially applicable. Freestyle skiing, slalom or carving, are multi axis movements that require more comprehensive 3D video systems in order to gather accurate data.

There have been several attempts to capture 3D images of skiers in both competition and more controlled situations. Different approaches exist for 3D video data collection in the field of skiing research. At least two cameras are commonly used for the reconstruction of 3D movements. Shimuzu (1983) published the first trials of 3D motion analysis of the turning technique on a simulation device using two cameras recording at 300 Hz. About ten years later a 40 meter capture zone was achieved using two panning, tilting, and zooming digital cameras positioned 60 metres apart on the side of the 1994 Winter Olympic downhill event. In this study the accuracy of digitized landmarks ranged from approximately 0.02 meters to 0.15 meters depending on the number of control points used for a particular frame, and the particular digitized landmark (Nachbauer & Kaps, 1996). Landmarks on the skiers' left side were not always visible from either camera, creating large errors, while landmarks such as the tail of the ski were not contrasted well in the picture, increasing the difficulty of pinpointing the location. A limitation of this technique for freestyle skiing, beyond specifically conducted testing sessions (e.g. Olympic Games), is that the commonly bulky clothing many athletes wear is not conducive to accurately locating anatomical landmarks.



Figure 16: 3D motion capture, the coordinate system of the angles to the direction of travel (Mueller & Bartlett, 1998).

In the more controlled setting of a specially prepared slope, the turning techniques of intermediate and experienced skiers have been investigated on specific kinematic parameters (Figure 16) (Mueller & Bartlett, 1998). A similar method of two panning and tilting cameras was used to determine and distinguish movement patterns between the different skill levels. No data was presented on the accuracy of the video system for this study. An investigation to develop optimized training protocols for slalom racers used a similar method to gather data. This data was used to develop and test two machines designed to mimic these movements (Raschner, Muller, & Schwameder, 1997). Many more studies have been conducted using a 3D approach including two high speed pan and tilt video cameras such as the investigation of landing movements in skiing (Gerritsen, Nachbauer, & van den Bogert, 1996), of the turning motion of skiers (E. Muller et al., 1998) and the take-off, flight and landing-phase in ski jumping (Greimel, Vimavirta, & Schwameder, 2009; Hildebrand, Drenk, & Muller, 2009; Virmavirta et al., 2005; Virmavirta et al., 2007). A frame rate as low as 50 Hz as chosen by Greimel et al. (2009) is a potential deficiency in measurement. For a high speed landing movement this

adjustment was not sufficient for kinematic analysis, as there were errors of joint centres amounting to two cm in a horizontal and three cm in a vertical direction.



Figure 17: Schematic illustration of an experimental setup of a calibration procedure during kinematic data acquisition (Mossner, Kaps, & Nachbauer, 1995).

Another option is to use stationary cameras, as Supej (2005) did, to assess the effect of changing snow conditions on slalom competitors' technique. This approach differs notably from those using tilting and panning cameras, because the recording image needs to cover a substantial distance resulting in a relatively small image of the skier. That in turn can lead to the need for bigger markers to pinpoint the anatomical landmarks as precisely as possible. Moreover, the calibration of the needed image can be challenging. There are several methods for appropriate calibrations presented within the literature. Supej and associates (2005) used two cubes with a base of one metre respectively. These cubes were situated wide apart in order to enhance the calibration accuracy. Mossner (1995) presented a calibration technique using panning and tilting cameras in order to allow for a larger image of the skier and thereby potentially improve the digitization accuracy. A total of 50 control points attached to rods of diverse heights were distributed throughout the testing slope being surveyed by a theodolite (Figure 17). Using at least six visible control points per frame resulted in a noticeable reduction of reconstruction error whilst calibrating each camera separately. Mean errors were reported to be less than 5 cm.

The same principle was used by Raschner et al. (2001). They used over 70 reference points and three synchronized cameras recording at a frequency of 50 Hz (Figure 18). The calculation of 3D joint angles and body positions was possible by employing the PEAK 3D system software in conjunction with a custom-made software developed by Drenk

(1993) for zooming and panning video data. This approach has subsequently been used in further studies (Gerritsen et al., 1996; Greimel et al., 2009; Mueller & Bartlett, 1998; Reid et al., 2009).



Figure 18: Carving trial in testing slope with calibration poles (Raschner, Schiefermueller, Zallinger, Mueller et al., 2001).

Another study from New Zealand validated a different video calibration technique using four stationary cameras (McAlpine & Kersting, 2006). This approach utilized a calibration cube and wand (Motion Analysis Corporation, Santa Rosa, USA) to improve measurement accuracy. The normal calibration volume of the cube was expanded from $0.75 \times 0.5 \times 0.75$ m to $3 \times 1.5 \times 1.5$ m with a wand extending from the cube for a series of still images. These images and the wand images were overlaid and served as the calibration object. The coordinate data were calculated both ways for several trials and compared to the Motion Analysis reference measure using eight cameras. A significant improvement of measurement accuracy was observed.

Greater accuracy could be gained in 3D imaging with the use of more than two cameras (Nachbauer et al., 1996). This would allow a clearer view of all landmarks and avoid some being blocked. If using several cameras for kinematic data collection a so-called 'genlock' system, plugged into each camera, commonly synchronises all the cameras. The optimal camera positioning is about 90°, but not more than 120° or less than 60° between the optical axes of the cameras (Bartlett, 1997; Mossner et al., 1995). Also, to gain the most accurate data, a camera position as close as possible to the field of data collection is advisable and panning should be minimized (Drenk, 1993). A non optimal camera position can lead to severe errors as shown by Mossner and colleagues (1995). In this

methodological study, limitations such as cable length led to errors of up to 20 cm. In his comparative study Raschner (2001) investigated carving turns and traditional parallel turns using three cameras with panning and zooming options arranged in a triangular configuration. In a study on turn characteristics and energy dissipation calculated from COM kinematics during slalom skiing, four panning and tilting cameras were used along the testing course (Reid et al., 2009). Klous and associates (2007; 2006b; 2006), for their methodological experiments, used a five camera set up for kinematic data collection at 50 Hz, which was accurate with error margins of one to two cm on a measuring image of 20m.

It remains questionable as to whether low sampling rates are sufficient for fast movements with a high angular velocity, or impact situations such as some freestyle movements or jumps. However, they might be reasonable for rather fluent movements with less abrupt changes and for fitful single segment motion and less angular velocity, such as carving on moderate slopes. Generally, kinematic data collections in an alpine environment need to be planned and conducted very conscientiously because of its challenging nature. Several sources of error can be encountered during data collection and data processing respectively, such as camera resolution, camera placement, volume location effects, camera combination effects, imprecision of digitization and target image distortion. Skin movement, mathematical model assumptions and anatomical marker placement are other sources of error that should be minimised (Dorociak & Cuddeford, 1995; Mossner et al., 1995).

The challenges mentioned can make it awkward to capture videos at times. Therefore some researchers prefer to use non-optical systems for kinematic data acquisition such as goniometry. A goniometer is a non-optical device that measures joint angles during performance. There are both advantages and disadvantages in goniometry. For instance on the one hand it is possible to collect data over a greater spatial distance, but on the other hand it is not possible to follow the total body movement of all segments. The earliest studies using a goniometer were conducted by an American research group (Kuo, Louie, & Mote Jr, 1983). They attached three goniometers to the knee in order to show the rotation of the tibia relative to the femur across the knee during skiing in terms of injury research. Mueller (1986) released one of the first comprehensive works about biomechanical analysis of skiing techniques. He also used several measurements for his technique assessment including two goniometers at the knees to measure the exact joint List of research project topics and materials

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angles. In another study, conducted by the same research group, Austrian ski instructors were tested using goniometers on the knees to quantify the magnitude and timing of flexion in each leg (E. Muller, 1994). With possible advances in technology, wireless data transmission from goniometers worn under clothing is undoubtedly possible and could avoid the problems already mentioned with respect to athletes' bulky clothing. Rauch (1988) further investigated the slalom technique by comparing two different slalom combinations.



Figure 19: Athlete instrumented with goniometer (Spitzenpfeil & Hartmann, 2004).

His method included the analysis of trajectory and ground reaction forces amongst others. Additionally, he employed goniometers and was thus able to show changes in knee joint angles during the runs. His analysis revealed a greater knee angle on the outside leg in the weighting phase as opposed to a smaller angle in the unweighting phase (Rauch, 1988). Further, goniometers have been used for the disciplines of cross country skiing, telemark and alpine ski racing (Nilsson & Haugen, 2004; Spitzenpfeil, Huber, & Waibel, 2006; Stoggl & Lindinger, 2006). An option to gather more comprehensive data of joint motion is to use two axis goniometers more suitable for movements that involve more than one plane. In a recently presented comparative work about different ski boots in slalom skiing such a device was employed to gain information about hip and knee flexion and extension as well as adduction and abduction (Petrone, Marcolin, De Gobbi, Nicoli, & Zampieri, 2009).

A further non-optical method to understand skiing motion is the use of a Global Positioning System (GPS). A GPS device enables the plotting of the skier's path and is

considered to have no major influence on the skier's performance due to its minimal size. Ducret (2005) first suggested GPS as an alternative motion capture tool and synchronized it with strain gauges in order to measure forces simultaneously. Other researchers presented their recent work on race performance and found the advantages of using a GPS device, such as collecting various parameters simultaneously like positioning, speed, heart rate data and time needed (Gomez-Lopez, Hernan, & Ramirez, 2009; Huber, Waibel, & Spitzenpfeil, 2009). Waegli et al. (2009) assessed the accuracy of a low cost GPS coupled with an inertial navigation system (INS) in comparison to a more costly technology for timing and slippage in giant slalom skiing. The low-cost system was considered sufficiently accurate and particularly beneficial for the analysis of the athlete's trajectory, timing, position, velocity, acceleration and orientation. The GPS was used to correct position errors measured by the INS system.

Another method to quantify kinematics in snow sports is the use of inertial sensors or a gyroscope. These systems are based on accelerometers and gyroscopic elements that measure the rate of rotation and were first utilized in 1983 for research in skiing (Kuo et al., 1983). Ohgi et al. (2007) used inertial sensors to investigate aerodynamic forces in ski jumping and Krueger and associates (2006) found a combination of an inertial measurement system (Xsens, Netherlands) and a dynamic measurement device to be useful for the analysis of technique training in elite downhill skiers. They mounted the sensor units on the ski, recording at a frequency of 50 Hz. The root mean square (RMS) of measurement error was reported to be 3° (Krueger et al., 2006). Scientists from New Zealand developed a new sensing technology combining inertial measurement units (IMU) with additional data from GPS, video and an RS-Scan insole system to determine full body kinematics and kinetics in alpine ski racers (Brodie, Walmsley, & Page, 2007). The GPS accuracy was indicated with a maximum error of ± 1.5 m over the observed race course, whereas the IMU orientation error was approximately 5°. The authors believed that the use of the combined system has the potential to provide information on possible avoidance of harmful body positions on the ski with regard to extreme knee torques (M. Brodie, A. Walmsley, & W. Page, 2008; M. A. Brodie, A. Walmsley, & W. Page, 2008). Supej (2009) recently presented his work on a combined 3D data capture technology using an Xsens inertial suit recording at 60 Hz and a GPS system (20Hz). He aimed to capture whole body 3D movements and to receive results shortly after the measurement in a slalom training course. Two participants wore the inertial sensing suit containing 16 inertial sensors. This measuring technology was evaluated as suitable for alpine skiing and

showed several advantages such as minimal effort in setting up and a prompt feedback for the athletes. However, as a drawback the system is invasive, which could be a limitation for using it on a regular basis (Supej, 2009). The following sub chapter will outline the existing kinematic studies in the area of freestyle skiing.

3.1.2 Freestyle skiing kinematics

Eight studies regarding mogul freestyle skiing kinematics have been found within this review. A study on mogul skiing technique has been conducted on three elite freestyle skiers filmed with two LOCAM high speed cameras at a frame rate of 200 Hz. The author suggested that the body position, immediately after impact with the mogul, with both the knee and the hip joints extended, as a possible vulnerable position for the ACL (Arndt & Milburn, 1994). Three markers on the foot, leg, thigh and torso were attached respectively, in order to define these segments in three dimensions. Unfortunately only a short abstract of this experiment is available so that the exact methods, such as the equipment used and its accuracy, marker size or camera position, are unknown. Schaff & Olbert (1996) compared a modified ski boot with a normal ski boot with regard to performance alteration. The study is limited by the number of subjects (N=2) and in that they used only one S-VHS video camera. This single camera was sufficient for the particular purpose of synchronising two different biomechanical measures, however, the investigators specifically recommended further investigations with advanced 3D video analyses in order to gain the most reliable data for such an assessment (Olbert et al., 1994). In another freestyle-related investigation two different ski boot models were again compared using two video cameras collecting footage at a frequency of 50 Hz. This data collection took place in a wave slope and was used for several projects with different emphases such as determination of joint angles in addition to kinetic parameters and EMG data (Friedl, 2007; Machens, 2006). The measuring techniques and results will be discussed more in depth within the current thesis (chapter 10.1).

In 2005 Swiss researchers undertook a detailed motion analysis project on freestyle ski jumping using 20 VICON 4 Megapixel infrared cameras operating at 120 frames per second (Lüthi, Böttinger, Theile, Rhyner, & Ammann, 2005). This project is unique with regard to the comprehensive testing equipment set up, investigated whether alternative jump techniques can potentially increase the number of twists per somersault. A high resolution, high speed, multi camera system system (in this case VICON) may be considered to be the Gold standard for accuracy in motion analysis techniques and is most

commonly used in a laboratory environment rather than in the field due to its complex adjustments and sensitivity to cold and light. VICON's accuracy was tested and is indicated with a root mean squared (RMS) measurement error of 0.047 cm to 0.183 cm (Richards, 1999). Thus, the results of this study can be considered very accurate.

A research group at the Oslo Sports Trauma Research Centre (OSTRC) validated a model based on an image-matching technique for 3D motion reconstruction from uncalibrated 2D video sequences in order to be able to analyse injury situations from video tapes (Krosshaug, 2002). One video sequence was integrated into the background of the animation model based on measured landmarks to create a virtual environment (Krosshaug & Bahr, 2005). This method was considered beneficial for a better description of the mechanics of sporting injuries, such as knee injuries in skiing. The same method is going to be implemented for 3D kinematic analysis in World Cup freestyle skiing (Krosshaug et al., 2002). Single video camera footage of injury situations was going to be prepared to perform a kinematic 3D analysis. The aim of that experiment was to classify and describe injury situations based on specific variables, such as the manoeuvre performed prior to injury, the position in the mogul course and body and limb postures. Desirable outcomes of that research proposal were the development of release criteria for ski bindings and the education of skiers in their awareness of injury situations and mechanisms. Preliminary results showed that reliable matching was gained using two cameras, however, it was difficult with only one camera. The same research group is currently implementing the FIS Injury Surveillance System, which aims to gather information on all the injuries from official training and competitions in World Cup events and World Ski Championships on several skiing disciplines, including mogul freestyle skiing (Oslo Sports Trauma Research Center, 2006). Currently, this comprehensive project is based mainly on an injury reporting system established by FIS. Additionally, in that context, the research group also analysed video footage collected at 50 Hz with a single video camera in order to evaluate the time of injury, the injury mechanism and the injury situation of ACL ruptures in mogul skiing (Heir et al., 2007). A Finnish group attempted to determine the angular changes of the knee joint and EMG activity during mogul ski turns among top level freestyle skiers (Riku & Miettunen, 2009). They utilised twin axis goniometers on both legs and found a total change in knee angles of $50-60^{\circ}$ during one turn with an average range from 84° to 161°.

For a thorough analysis into the mechanics of skiing, kinetic measurements are another crucial biomechanical component. They can provide important information on understanding and improving skiing techniques as well as specific equipment. The next sub-section will review the most important studies in the field of kinetic analysis in skiing.

3.2 Kinetic analysis

Kinetics describes the act of moving, specifically the forces and interactions that produce motion. Mechanical assessments of skiing techniques have been investigated previously with regard to segmental movements, external forces and moments using biomechanical models. As opposed to laboratory based investigations, measurements of kinetic parameters in snow sports are particularly challenging due to the unpredictable environmental circumstances such as cold, wind, changing light and surface conditions. Measurement devices are commonly attached to moving equipment further complicating method development. Thus, the results are often subject to certain limitations and interpretations must usually be treated with caution. The following sub chapters will delineate the history of kinetic measures in skiing including previously conducted kinetic investigations and their methods.

3.2.1 Kinetic studies on Alpine skiing

In alpine skiing, efforts to measure ground reaction forces (GRF) have been reported since the mid-sixties (Outwater & Woodward, 1966). Karlson et al. (1978) identified the necessity of measuring the acting forces in skiing. They developed a testing ski boot to measure forces at the sole of the foot as well as at the shaft of the boot. Unfortunately results of these tests were not published. The book 'skiing mechanics' is the English framework of biomechanical analysis in the area of skiing. It contains a comprehensive background about movement patterns and forces in skiing as well as explanations about ski design and properties (Howe, 1983). A number of articles from Japanese research groups were published in the 1970's and 1980's. Shimizu (1980; 1981) identified, in a laboratory based investigation, the reaction time for up-unweighting to be 90 ms slower compared to a down-unweighting movement following an optical stimulus. That research also analysed the GRF of leg flexing and extending at different speeds using force sensors in the ski boot.

Knowledge of kinetic parameters are vital for the development and improvement of equipment (Wunderly, Hull, & Maxwell, 1988) and for the understanding and

optimisation of skiing techniques (Brueggemann et al., 1991; Kassat, 1985; Mester, 1988). Interfaces to which a measuring device can be attached are those in the slope (Raschner, 1990; Vaverka, Janura, Salinger, & Brichta, 1993), between the ski and the , between the binding and the boot (Kiefmann, Krinninger, Lindemann, Senner, & Spitzenpfeil, 2006; Wimmer & Holzner, 1997), and between the boot and the foot (Hall, Schaff, & Nelson, 1991; Kiefmann et al., 2006; Lafontaine, Lamontagne, Dupuis, & Diallo, 1998; Maxwell & Hull, 1989a; E. Muller & Schwameder, 2003a; Quinn & Mote, 1993; Raschner, Muller et al., 1997; Schaff & Olbert, 1996; Schaff, Schattner, & Hauser, 1987). Figure 20 shows an example of a measuring device positioned at the interface between ski and binding. The following paragraphs will provide an overview of kinetic studies using different devices at the mentioned interfaces and briefly discuss this information with regards to the applicability to the current project.



Figure 20: Instrumented skis with force plate between binding and skis and local coordinate system (Schwameder et al., 2000).

Raschner (1990) mounted a force plate on a custom built test ramp for investigations of single and double leg starting techniques in ski racing. The plate was positioned in the pole planting area of the start area and measured both the vertical and horizontal forces. Some aspects were found for a particularly beneficial evolvement of the forces such as the path of the whole system's centre of mass, the horizontal position and the body posture at start of time measurement and the position of the horizontal force application point. This setup was appropriate for the intended data acquisition of performance parameters at a certain spatial point, specifically the start. However, this approach is not applicable for data collection during execution of consecutive turns.

Some researchers collected vertical force data from below the skis by mounting force bars into the ski jump take-off table (Segesser, Neukonn, Nigg, Ruegg, & Troxler, 1981; Vaverka, 1987; Vaverka et al., 1993; Virmavirta & Komi, 1989, 1991, 1993a, 1993b). For future research Virmavirta & Komi (1993) recommended to additionally measure horizontal forces at the binding. That way testing could benefit from the possibility of collecting data over a long distance.

Formerly, most researchers used the interface between the ski and the binding for kinetic measures. Mueller (1991) developed a testing ski to measure vertical GRF using force sensors beneath the medial and lateral part of the forefoot and the heel. The total forces experienced by the subjects varied depending on the environmental and snow conditions (e.g. steep vs. flat, icy vs. grippy etc.). Subsequent research used the same measurement device for the quantification of the slalom and giant slalom technique (Nachbauer, 1986, 1987, 1988).

An American research group has reported on two different force transducer designs (Hull & Mote Jr, 1980; Kuo et al., 1983; Louie, Kuo, Gutierrez, & Mote, 1984; Quinn & Mote, 1990, 1993; Yee & Mote, 1996). They aimed at measuring the rotation of the tibia relative to the femur across the knee during skiing. Initially, a single test ski on the left leg with a six degree-of-freedom pedestal dynamometer instrumented with 24 strain gauges has been used. The resolution was between 4 N (F_x , F_y), 0.1 Nm (all moments) and 20 N (F_z). A telemetry system was housed in a backpack of 5.8 kg total weight worn by the subject and used to transmit all data to the ground station. For the more recently revised design, a T-shaped shear panel element (SPE) was used instrumented with four strain gauges (Quinn & Mote, 1990). This dynamometer had dimensions $14 \times 9.5 \times 3.2$ cm and weighed 17 N. The maximum range was indicated with 1300 N (F_x), 1000 N (F_y), 4000 N (F_z), 100 Nm (M_x and M_y) and 60 Nm (M_z). Yee and Mote (1996) and Quinn and Mote (1993) used the same device for their studies on leg loading in skiing. Information about validity of the technique are not given.

Another research group introduced a first generation binding system used to measure boot loads (MacGregor, Hull, & Dorius, 1985). This system consisted of four octagonal half strain rings instrumented with 24 strain gauges, an integral dynamometer release mechanism and a micro computer based controller. Both laboratory and field evaluations of the system revealed major limitations with regard to measurement accuracy with an

error margin of 10-15% as well as other deficiencies. Motivated to overcome the mentioned problems, Wunderly et al (1987) developed a second generation binding system to measure GRF in skiing with rigid sensing elements along a single axis. These sensing elements have been mechanically uncoupled in order to minimize the cross talk. The device was 40 mm high and has been used for other studies on GRF in skiing, collecting data at 200 Hz with greater accuracy than the previous model (Maxwell & Hull, 1989a; Wunderly et al., 1988). Also, in the late 1980's Menke and associates (1987) used a strain gauge force platform mounted underneath the ski binding in a laboratory environment to analyse the muscle activity and vertical forces under the heel and forefoot as well as the longitudinal force originated from the ski boot. Unfortunately, no indications about the dimensions or accuracy of the device were given.

More recently, miniature strain gauges have been used between the ski and the binding. The standard binding plate was replaced by the device causing a 6 mm elevation compared to normal skis. The system enabled the measurement of all forces and moments along three axes and must be placed very precisely due to its small dimensions (Vodickova, Lufinka, & Zubek, 2005). A set of amplifiers and compact flash disc for recordings have been custom-built with a single chip microcontroller powered by batteries. The overall error of the resulting forces was found to be appoximately 7%. The group analysed the load on the inner and the outer leg during open versus closed carving turns. Klous et al. (2006b) conducted a methodological study to validate kinetic measurements for both skiing and snowboarding. To collect 3D kinetic data they used mobile force plates mounted between the binding plate and the binding containing piezoelectric crystals that could measure dynamic changes at 100 KHz (Klous, 2007). The dimensions were 229.5 \times 64×36 mm with a weight of 0.9 kg. Additionally, the participants carried a backpack with four charging amplifiers and two PDA's for data storage, which added to a weight of 2.5 kg (Klous, Schwameder, & Mueller, 2004). Several validation tests have been conducted and the measurement accuracy was sufficient for outdoor applications with a mean error of 4.6% at low forces (<292N) and only 0.3% at higher forces (>292N). The average measurement error for the associated moments were between 4.0% and 8.3% (Stricker, Scheiber, Lindenhofer, & Mueller, 2010).

The influence of the riser height on the kinetic variables in giant slalom was investigated using a specific testing ski boot instrumented with a strain gauge beam arrangement (Niessen, Mueller, Wimmer, Schwameder, & Riepeler, 1999). The sensors were decoupled, temperature compensated and capable of measuring both compression and tension forces applied at four points at the toes and the heel. That way the frontal and sagittal moments can also be calculated. A Biostore datalogger (Biovision, Frankfurt, Germany) was worn by the participants on a belt recording a maximum of 30 seconds of skiing, which was transmitted to a docking station after each run (Figure 21).



Figure 21: a) Measurement equipment/ testing boots; b) measurement of vertical forces beneath boot at four application points under the toes and the heel (Niessen et al., 1999)

Three different riser heights were tested (no binding plate, 1cm plate, 2 cm plate) and it was reported that finishing time decreased with greater riser height. However, both forces and moments did not increase significantly after being normalized by time.

The most crucial premise for such measurement devices is to limit the impact of the measurement units on riding technique while being precise. Hence, with regard to measurement systems there has always been a trade-off between accuracy of the testing and potential impairment of the skier's performance. Thus, two force measurement devices designed for carved slalom use were tested with regard to its sensitivity to constraint forces such as the mentioned bending effects (Wimmer & Holzner, 1997). The researchers used the interface between the binding heads and the ski for one device (Figure 22,b) and between the binding and the boot for the other device (Figure 22,a).



Figure 22: a) ski boot with fixed adapter bars; b) sole plate and sensor plate (Wimmer & Holzner, 1997).

For the first device Figure 22,b), two sensor plates weighing 450 g with a height of 7 mm in and four laterally directed beams instrumented with strain gauges were placed under the toe and heel pieces of the binding. The second device consisted of four longitudinally aligned beams with strain gauges attached beneath the boot sole. The device altered the skier's stance by 16 mm and had a total weight of 990 g. A half bridge was applied on each sensor to compensate for shear forces and temperature. Additionally, a statically determined fixation was used, specifically a fixed bearing at the heel and a movable bearing at the toe to allow for relative motion and thus avoiding constraint forces within the four transducers. Laboratory based results demonstrated that the device between binding heads and ski measured inaccurately with errors of up to 300 N per sensor during flexion tests. According to the authors, ski bending can cause undesirable noise in the form of the transmission of an additional torque. This occurs if the sensors are placed to inhibit the rotation of the binding when following the bending line of the ski (Figure 23).



Figure 23: Undesirable noise can occur with ski bending as constraint mechanism (Wimmer & Holzner, 1997).



Hence, the results were probably distorted as the device was measuring large forces even though no vertical forces were applied. Therefore, only the device attached underneath the ski boot was concluded to be applicable to detect realistic values. However, the need to validate measurement devices in order to guarantee valid results was confirmed by this study.

Kiefmann and colleagues (2006) developed a sophisticated six component dynamometer to be attached at the interface between the binding and the boot in order to avoid transmission of undesirable noise originating from the bending of the ski as shown by Wimmer & Holzner (1997). This ski force plate was unique in its adjustability to different ski boot sizes and skis and its wireless data transmission. It consisted of six onedimensional force sensors and a mechanical uncoupling device. Transducer elements designed as shear beams attached with strain gauges were integrated and capable of measuring a load range of 6 kN in the vertical, 2 kN in the transverse (across the ski) and 1 kN in the longitudinal direction (along the ski) (Kiefmann et al., 2006). The device weighed 2 kg and was 36 mm high with an accuracy of \pm 4 N and \pm 0.1 Nm (chapter 7.1.1). Their revised technology should assist to overcome the limitations of previous testing devices that were often too large, inaccurate and usually non-adjustable. It was also supposed to improve the flexibility and accuracy of recordings.

As mentioned above, another option for kinetic measurement is the interface between the foot and the boot, specifically the inside of the boot. This type of measurement, specifically the pressure sensitive insoles, is common in sports, such as running (Weist, Eils, & Rosenbaum, 2004), and potentially the least restricting to the athletes' movements due to its thinness. However, it is limited in that it is a unidirectional measurement and only capable of measuring pressure or vertical force respectively. Technology advances enabled researchers to conduct measurements of this type from the early to mid 1980's (Schattner, Asang, hart Hauser, & Velho, 1985). Formerly, capacitive measuring mats, attached to the skin of the participants, were used and carried data storage units weighing approximately 8 kg, whereas recently, pressure sensitive measurement equipment has improved and data loggers only weigh half a kilogram. The utilisation of such measurement devices has been established to test equipment improvements and has delivered valuable insights into ski boot designs. This technology revealed major advantages of conventional boots over rear entry boots with regard to the distribution of tibia pressure (Schaff, Senner, & Kaiser, 1997).

Some early studies measured the pressure distribution inside the boot to verify the applicability of these new measurements for elite skiing. These were developed using hydrocell technology which is the most appropriate in terms of reliability and reproducibility, even under rough conditions (Hall et al., 1991; Schaff, Hauser et al., 1987).

Figure 24 displays an example of the technology.



Figure 24: a) participant instrumented with data logger in belt; b) pressure insole (Raschner, 1997).

Schaff and colleagues (1997) used several measurement systems such as normal PAROTEC insoles with 16 sensors, a single sensor system called 'swing beep' and a highly sophisticated measurement sock. The latter was attached with sensors beneath the foot as well as around the lower leg, the instep and medially and laterally at the foot. The common pressure sensitive insoles are usually instrumented with piezoresistive hydrocells as a pressure transducer measuring at a frequency up to 250 Hz. The 'swing beep' system serves as feedback for students and provides an acoustic signal once the heel pressure exceeds a pre-determined value. Krueger and associates (2006) used PAROTEC insoles to validate a testing procedure including the determination of the edging angle and the GRF in alpine skiing. Their insoles contained 24 sensors collecting data at 150 Hz. The maximum error of measurement has been specified by approximately 20 % (Spitzenpfeil, Hartmann, & Ebert, 2002). Nevertheless, the system was rated as useful for application in

training technique assessments. Insole measurements were also used for biomechanical analyses in ski racing. Raschner et al. (2001; 2001) used insoles with 99 capacitive sensors recording at a frequency of 50 Hz to analyse carving turns compared to traditional turns. A graphical illustration can provide rapid feedback on the investigated parameters. In this case, a more distinct backward leaning in the steering phase of carved turns was found, followed by a forward movement in the next initiation phase (Figure 25).



Figure 25: Pressure distribution of the outside foot during a right turn in carving (left) vs. traditional skiing (right) (Raschner, Schiefermueller, Zallinger, Hofer et al., 2001).

Spitzenpfeil et al. (2006) investigated the mechanical load in alpine ski racing and the implications for safety and material considerations. PAROTEC, PAROMED insoles were used to subsequently calculate GRF's of up to 2000 N. Unfortunately, no further technical details about the measurement equipment were given. The first study to use this type of measuring device (PAROMED) were Virmavirta and Komi (2000) using 16 pressure sensors to monitor force distribution in ski jumping. A well balanced plantar pressure distribution was observed in the in-run for all participants.

Another system of the same technology is the NOVEL PEDAR insole system, which has previously been used for ski racing (Raschner, Schiefermueller, Zallinger, Hofer et al., 2001), recreational skiing (Lafontaine et al., 1998), f cross-country skiing (Stoggl & Lindinger, 2006) and ski jumping (Schwameder & Mueller, 1995). According to Mueller & Schwameder (2003a), however, the PAROMED method of measurement was characterized by a remarkably higher sampling rate in comparison to the PEDAR insoles at that time. It needed to be adjusted individually and very precisely to produce representative data. New Zealand researchers used an RS-scan integrated in the newly developed 'Fusion Motion Capture' to determine plantar pressures during ski racing. The authors reported that this technology can provide insight into possible stance alteration
options to reduce high knee torques or aid preventive training programs (Brodie et al., 2007).

The following section will address the limited research on freestyle skiing kinetics.

3.2.2 Freestyle skiing kinetics

Freestyle skiing exhibits a high incidence of knee injuries for both competitors and recreational skiers (Inoue et al., 2006; Krosshaug et al., 2002). Two studies on both kinetics and kinematics in mogul skiing were presented within the literature so far. Schaff & Olbert (1996) examined the loading of the foot sole with respect to the ski boot design while skiing moguls using pressure sensitive insoles, each with seven piezoresistive sensors in hydro cells. The measurement frequency was 100 Hz and the data logger was worn by the participants as a belt in order to guarantee minimal impairment of the performance. They used modified ski boots which allowed for greater ankle flexibility than normal ski boots and revealed a higher pressure on the forefoot with modified equipment, suggesting a greater forward lean. The pressure on both heels could be minimised by approximately 35% over a distance of seven moguls. The authors assumed this could suggest a reduction of the impact on the knee joints of approximately the same percentage. The study is limited by the number of subjects (N=2) and they used an S-VHS video camera which could synchronise the footage with the kinetic data. However, they were not able to create a precise 3D description of the forces and moments applied to the human body. The investigators recommended further investigations with advanced three dimensional video analyses and reliable kinetic measurements to gain knowledge about tissue loading in mogul skiing (Schaff & Olbert, 1996).

Kryszohn and associates (2005) compared two different ski boot designs measuring GRF during mogul skiing with a purpose built measuring binding. The sensors for this binding were located between the binding and the ski. The tested runs were documented by video recordings and the data were used for utilising a computer knee model. Further details of the measurement device were not given because only an abstract is available. However, personal communication with an involved researcher revealed that the use of the force plates was not accepted by the participants due to the weight and height being beyond tolerance levels (Boehm, 2008). Additionally, the measurement unit was not considered precise due to the known limitations such as transmission of undesirable noise originating from the bending of the ski.

As noted in 3.1.2 all other freestyle skiing related studies were of an epidemiological, psychological or observational nature. Further, there are some articles or abstracts in ski magazines or on the Internet that report experiences anecdotally (Frejka, 2009) or with technique instructions/training recommendations (Mahre, 2003; McIntyre, 2003). These are potentially helpful for interested skiers, but scientifically irrelevant due to a lack of reliable data. A particularly interesting and potentially useful tool to enhance the development of injury prevention and equipment improvements is the emerging scope of computer simulations. The next section will briefly introduce the principles and possibility of computer simulation, specifically, inverse and forward dynamics in skiing and other sports.

3.3 Computer simulation – a promising approach to aid injury prevention in skiing?

The investigation of human movements using computer models have been well established within the last twenty years. This section provides a brief overview of some of the general principles in modelling, existing models and of the current progress of computer simulations in the area of skiing.

Research in human locomotion is, to a large extent, based on observation and experimentation. However, it is well known that an advanced knowledge base cannot be obtained from field tests alone. Creating and verifying mechanical models and simulations of movement is one area with a large potential to understand the body's mechanical function and internal loads that result from sporting movements. These methods are also used to optimize athletic performance and to improve equipment design. In the Oxford English Dictionary models are described as "a simplified mathematical description of a system or process, used to assist calculations and predictions". Generally, the reality (e.g. performance) is monitored and measured and models depict the interrelation between the monitored action or impact and the system's reaction (Senner, 2002). Advantages of such models are that they can provide the fundamental understanding of the body's function and insight into joint and tissue loads, and how these are altered through specific changes such as modifications in equipment or performance technique. Moreover, models can potentially anticipate results even if natural or anatomical capacities are exceeded. This is a crucial aspect in biomechanics as it would be unethical to use any methods that could jeopardise a participant's health.

Table 1 displays a list with examples for commercially available computer software for multibody systems and its providers.

| SOFTWARE NAME | DISTRIBUTORS |
|---------------------------------------|---|
| SimPack™ | INTEC GmbH, 82234 Wessling, Germany |
| SIMM | Musculographics Inc. |
| MD Adams TM | MSC Software Corporation, St. Ana, CA, USA |
| Madymo ^{тм} | TNO Automotive Safety Solutions, Delft, Netherlands |
| Pro/Engineer Mechanica [™] | PTC Waltham, MA, USA |
| Anybody Modelling System [™] | Anybody Technology A/S, Aalborg, Denmark |

Table 1: Commercially available computer simulation software and their distributors.

SIMM was the first graphics based software for development and analysis of musculoskeletal models and emerged in the early 1990's (Delp et al., 1990). This software package was well established and had been used by various researchers (Anderson & Pandy, 2001; Higginson, Zajac, Neptune, Kautz, & Delp, 2006). A more recently developed modeling system is the Anybody Modelling Software[™] (Anybody Technology A/S, Aalborg, Denmark), which has been used for the estimation of muscle forces and joint contact forces (de Zee, Hansen, Wong, Rasmussen, & Simonsen, 2007; Rasmussen, 2008). This modeling software will be described in depth in (chapter 7.3) as it has been used in the current project.

Two different models are generally used: physical models and mathematical models. Physical models specify all objectives and are predominantly mechanical appliances or constructions that recreate certain properties of the real system, e.g. 'crash test dummies'. The major disadvantage of physical models for skiing is that they are passive and muscles cannot be included so recovery attempts in out-of-balance situations cannot be studied. Mathematical models use a mathematical description of real events based on physical laws. The current work will involve the use of mathematical models to study the body movements involved in skiing. There is a distinction between two different approaches within mathematical models, 1) 'inverse dynamics' and 2) 'forward dynamics'. The slightly older and most utilised approach is inverse dynamics and involves processing experimental motion data, usually with external forces (e.g. GRF) to compute the net torques developed at joints by the muscles (Zajac & Winters, 1990). An inverse dynamics

method attempts to infer the cause of the movement from the kinematic outcome, whereas a forward dynamics solution estimates a movement result by manipulating the causes of the movement, i.e. muscle/ joint forces, torques etc. Forward dynamics or direct dynamical approach involves model-driven simulations of the movement task, and demands a mathematical description of the system dynamics and of the performance goal associated with the motor task. The latter controls the muscle activation and is the more sophisticated and advanced approach, however, it is based on several assumptions and simplifications. Therefore, a perfect solution for simulations is difficult to establish; sometimes the criterion of the motor task or the assumptions in the model structure need to be scrutinised and, in general, a 'nearly optimal' solution may suffice (Zajac & Winters, 1990).

Models can represent a comprehensive system involving numerous systems, a single joint, or more specifically a ligament within the joint (Figure 26).



Figure 26: Biological structures and associated modelled multibody systems in specific body parts and sample applications in sport science.

There are several detailed knee models present within the literature (Bendjaballah, Shirazi-Adl, & Zukor, 1997; T. S. Buchanan, Lloyd, Manal, & Besier, 2005a; Delp et al., 1990; Delp, Loan, Basdogan, & Rosen, 1997; Ehuis, 2004; Heegaard, Leyvraz, Curnier, Rakotomanana, & Huiskes, 1995; Hefzy & Cooke, 1996; Hefzy & Grood, 1988; Lehner, 2007; McNally & Arridge, 1995; Pennock & Clark, 1990; Shelburne & Pandy, 1997). According to Senner (2002) there are certain decisive criteria for the selection of an appropriate knee model for a specific application: it must be three-dimensional, include all essential structures and must incorporate the affect of the most important muscles; it requires realistic size and geometry; compatibility with models (e.g. skier), must be guaranteed and eventually has to be available. Such models are usually custom made in certain projects and are not available for the general public or are commercially developed and need to be purchased.

First attempts to simulate a turn were performed by Lieu and Mote (1985) and Renshaw and Mote (1991). They used skidding forces first described by Lieu and Mote (1984) for the machining of ice to investigate the steady-state solutions of a turning ski. Modeling is particularly useful when investigating the biomechanics of performance whilst airborne. In the field of skiing, both inverse and forward dynamics approaches have been used. Ski jumps were investigated to determine the posture during flights resulting in the greatest distance or the effect of the transition at take-off on jump distance (Denoth, Luethi, & Gasser, 1987; Hubbard, Hibbard, Yeadon, & Komor, 1989; E. Muller & Schwameder, 2003b; Remizov, 1984; Ward-Smith & Clements, 1983). A wind tunnel investigation, using a model on the effect of the V-style to distance, confirmed a positive effect (Seo, Watanabe, & Murakami, 2004; Watanabe & Watanabe, 1993). Other ski jump studies focused on safety and the optimization of hill profiles and ramps using computer simulations (W. Muller, 1996; W. Müller, Platzer, & Schmölzer, 1995). However, a drawback of computer simulations is that they are based on certain assumptions. Mueller et al. (2003a) stated that the use of different models in investigations of the optimal flight position led to substantially different results. Unfortunately, no indications about the accuracy or the validity of the computer models are given.

Hermsdorf et al. (2008) recently developed a detailed biomechanical multibody model called 'Jumpicus'. Kinematic parameters of real jumps can be investigated as well as forward dynamic simulations accounting for changes in equipment and the athlete's performance. For instance, the effect of specific take-off movements on vertical take-off velocity and angular momentum at the lip of take-off were measured. The model has been validated using 3D motion capture data and a dynamic measurement device measuring jumps in vivo (Hermsdorf, 2010; Hermsdorf et al., 2008). A custom made knee model has been used to suggest that bindings with a pivot point at the front of the foot as well as the usual binding centred in the heel is a method to prevent ACL injuries (St-Onge, Chevalier,

Hagemeister, van de Putte, & de Guise, 2004). It was reported that a binding with two pivot points, at the front and at the back, distributed the ACL load and might be a solution to reduce the frequent occurrence of ACL ruptures especially through the phantom foot mechanism. A MATLAB script has been developed for an inverse dynamics approach on knee joint loading during carved turns in comparison to skidded turns revealing that higher vertical knee forces were acting on the outside leg during carving (Klous et al., 2007). However, knee moments and forces were higher for the inside leg in skidded turns, thus disproving the popular believe that general knee joint loading was larger in carved compared to skidded turns. No information was indicated regarding the model that the script incorporated or how the load was calculated.

Van den Bogert et al. (1999) compared joint loading in walking and running in six different skiing situations such as large turns on a flat slope, short turns on a flat slope, large turns on a steep slope, short turns on a steep slope, cross country skiing and mogul skiing. They used accelerometers to collect kinematic data that was used as input data for an inverse dynamics model to compare the different types of sports and specific movements with regard to tolerance for patients with hip replacements. Walking was harmless and had relatively low peak joint contact forces and cross country skiing and moderate skiing with long turning radii on flat slopes showed a relatively low loads, but there were higher medio-lateral and anteroposterior forces than walking. More challenging skiing movements were not recommended for hip replacement patients. Despite this, little is known about higher loads in transverse directions on artificial hip joints, hence why there is no definite conclusion concerning the effects of moderate skiing and cross country skiing on hip prostheses.

Gerritson et al. (1996) used a direct dynamics simulation model to analyse possible ACL injury mechanisms in downhill racing jumps (Figure 27).



Figure 27: Two-dimensional skeletal model of a skier (Gerritsen et al., 1996).

In addition to multibody dynamics and muscle dynamics, their model also included the ski-snow-interaction, which is difficult to represent in computer simulations. A slight simulated balance disturbance in conjunction with a recovery attempt by quadriceps muscle contraction led to remarkably higher peak forces at the ACL of 1 350 N. This is within the range of failure loads as compared to the simulated normal landing movement with 589 N. According to the authors, the quadriceps activation only contributed to 25% of this load whereas the contribution of external forces was 75%. The model was evaluated and was realistic to assess for potential injury situations based on the accuracy of the reproduction of a typical landing movement (Gerritsen et al., 1996). However, as a shortcoming, this model was only two dimensional and thus was not able to account for internal/external rotation and adduction/abduction of the tibia, which could have a large influence on ACL loads (Gerritsen et al., 1996). According to the authors conscientious validations of computer models are in demand.

A more recent study investigated a 3D forward dynamic musculoskeletal model to determine if sagittal plane knee loading can cause ACL injury during sidestep cutting movements (McLean, Huang, Su, & Van Den Bogert, 2004). They assumed an anterior drawer force of more than 2000 N as the threshold for ACL injury and reported that anterior drawer forces encountered in sidestep cutting were not large enough to injure the ACL. Valgus loading, however, was revealed to be more likely to expose the ACL to serious injuries, particularly in females. Advanced 3D knee models such as this are desirable for investigations on potential injury mechanisms in skiing.

V=vt=List of research project topics and materials

A range of modeling techniques has been used in sports such as gymnastics and trampolining that could be applicable to freestyle skiing. Studies of gymnastic movements can be used to investigate various methods of freestyle skiing. Many disciplines of gymnastics involve generating forces at take-off to allow for execution of particular aerial manoeuvres, as in freestyle skiing. Koh and Jennings (2007) predicted the optimal execution of the Yurchenko layout vault² and used mathematical modeling to determine take-off variables, such as body angle and angular momentum leading to its execution. According to the authors the model accurately evaluated the examined task (Koh & Jennings, 2003). However, no data about any validation of the model was presented.

Computer modeling has been used for other studies in gymnastics to determine maximum variation in take-off angular and linear momentum that may result in a successful landing from a layout somersault (King & Yeadon, 2003). It was found that variations of up to 8% could be adjusted for by alterations within flight. This could be very useful for freestyle skiing as the take-off areas encountered are not always the same or of uniform consistency. The simulation model was validated by comparing the simulation data with the actual field test data set. An average difference of 1% in linear and angular moments and 5° in the joint angles during the contact phase showed satisfactory accuracy (Yeadon & King, 2002).

The same authors investigated whether a triple layout somersault was possible. They concluded that it would be possible if both linear and angular velocities were maximized, in combination with an altered activation of the five modeled joints (King & Yeadon, 2004). However, a major shortcoming of these studies is they only investigated planar motion, thereby reducing its transferability to freestyle skiing as all high scoring tricks in skiing involve off-axis rotations.

A different study investigated the ability to adjust shoulder torques to make corrections in flight while maintaining lower body kinematics so to complete a successful landing (Requejo, McNitt-Gray, & Flashner, 2004). The equations of motion were comprised of a set of seven second order differential equations. The authors validated the model with experimental data to determine contribution of multiple error sources to the accuracy of the model. They determined the complexity required for a model that accurately emulates

² A Yurchenko layout vault is popular in women's gymnastics and consists of a round-off onto a springboard, a flick-flack onto the vaulting table, and then a layout backflip off the table.

dynamic behaviour. Multijoint models with varying numbers of segments were evaluated. Errors during both modeling and digitization contributed large violations in the simulation. Therefore the sources of error for experimentally based dynamic models need to be quantified and minimized prior to employment due to several sources of error (Requejo, McNitt-Gray, & Flashner, 2002). Again this study is limited by the fact that it only examined planar movements. Nevertheless, the idea of investigating the ability to adjust mid-flight has great potential for the study of freestyle skiing because it is a relatively open skill and can be affected by many parameters and conditions such as the wind.

Hraski and Mejovsek (2004) tested the generation of angular momentum at take-off in a backwards somersault. It was found that the majority of angular momentum was generated by the trunk and the shoulders. It would be of interest to know if this is valid in skiing given the added weight of boots and skis.

An advantage of modeling is that it enables potentially dangerous situations to be explored allowing investigations into injury mechanisms, without harm to participants. However, a major limitation is that it only represents an estimation of the real situation. The complicated aspect of modeling is that it requires prior knowledge of parameters that can be entered to create the formulas. Hence, it is important to carry out kinematic and kinetic studies, in detail, to have precise values for building models. After introducing the general idea and prospect briefly, the scope of computer modeling is going to be discussed in more depth in subsequent sections (chapter 7.3).

3.4 Summary

The results of the reviewed literature in this chapter are predominantly from recreational alpine skiing, alpine racing and ski jumping as the majority of biomechanical investigations were conducted in those particular disciplines. Pressure insoles have often been used in alpine racing for direct feedback to the shifting of the centre of pressure (CoP). It is very user friendly and does not interfere with the athlete, however, is only capable of measuring vertical pressure and thus not appropriate for comprehensive 3D motion reconstruction. Force plates below the binding have the potential for 3D data acquisition, however, are often criticised for being bulky and thus significantly impair the athlete due to its weight (Boehm, 2008). Additionally, these measuring devices often did not decouple the ski's bending from the measurement unit and thus transmitted undesirable noise (Wimmer & Holzner, 1997). Force measurement devices between the

ski boot and the binding came off better within this literature review and carry the potential of optimised data acquisition during consecutive turns (Kiefmann et al., 2006). This will be discussed later in the thesis (7.1).

Previously, minimal work with limited measurement equipment has provided inaccurate data on the kinematic and kinetic parameters of freestyle skiing. However, the technological developments in the recent decades should not be ignored as 3D kinematic data collection based on multiple camera systems is possible and GRF data have been measured using complex custom-made force transducers and pressure insoles. However, it is vital to ensure that measurement equipment does not impair the skiing technique. Hence, prior to testing it is the primary goal to minimise the effect of the devices on skiing technique and to establish the extent of the influence.

There are still many gaps of knowledge concerning appropriate injury prevention strategies and the most advantageous techniques and equipment in skiing, particularly freestyle skiing. Furthermore, the current knowledge is primarily based on assumptions and due to the many measurement limitations and inaccuracies could be misleading. Some researchers attempted to assess joint loading on the lower extremities in alpine skiing, but a useful 3D movement analysis in freestyle skiing needs to be conducted. The prevailing lack of structural 3D movement analysis in complex disciplines such as freestyle skiing is due to the repeatedly mentioned challenges that are encountered in the field and the large complexity of the costly set ups. Further advancements in technologies will presumably allow for more comprehensive and precise studies in-situ. The goals of the current project arise from the previous literature review and are outlined in the following chapter.

Chapter 4: Aims and Outline

4.1 General research intention

This chapter will outline the idea behind this research project including the major aims for the studies. These aims have been formulated after the extensive literature review on skiing injuries, injury mechanisms, technical aspects of skiing, equipment tests, injury prevention strategies, biomechanical methodology and modeling techniques in the area of alpine skiing. Three consecutive studies are included in the current project. These studies have been progressively designed to incorporate the findings of each subsequent study.

As described in chapter 2.2 there are different risk factor categories and injury mechanisms that are sometimes overlapping or occurring together. Figure 28 displays the risk factors and events that lead to knee injuries. The current project is focused on the effect of ski boots on the ski stance in freestyle skiing and the resulting knee joint forces. Although this aspect belongs to the extrinsic factors, intrinsic factors are of interest as muscle forces are included in the model calculations as further illustrated in chapter 7.3.



Figure 28: Overview of intrinsic and extrinsic risk factors and inciting events for knee injuries during skiing.

Shealy (1993) stated that equipment should match the required skiing technique for specific disciplines such as downhill racing or mogul skiing. However, it is more common for skiers to adjust their skiing technique to the available equipment. The restriction of the body's natural range of motion during sport performance, such as the ankle fixation in a conventional ski boot, is critical concerning the possible overloading of anatomical

structures in the knee (Schaff & Olbert, 1996). Mogul skiing consists of bending and straightening the legs in order to absorb the moguls appropriately whilst retaining snow contact. However, the range of movement for that squatting task is highly restricted by the stiff ski boot and the athlete is forced to bend in an awkward backward position (Figure 29,a) which potentially endangers the knee joint (Senner, Lehner, Wallrapp, & Schaff, 2000). The usage of a modified ski boot that allows for a significantly greater dorsiflexion in the ankle joint may assist in the attainment of a more advantageous position of the body's centre of mass with respect to the neutral position. The neutral position is defined as the middle position with regards to the anteroposterior direction, with the body's CoM above the base of support (Bell, 2001; Kassat, 1985, 2000). Therefore, freestyle skiers can potentially squat down in a natural way to use their own body as a damping system to absorb the impact of the moguls using their ankle and knee joints.

This intervention is expected to alter the lower limb and knee joint alignment and thereby the neutral position can be maintained rather than regained as this approach prevents an overbalancing situation (Figure 29,b).



Figure 29: a) Forward lean position with the CoM above the base of support b) Distinct backward lean with stiff ski boots

The general purpose of the current project is to identify the mechanical effects of flexibility changes in the ankle joint of ski boots on the movement patterns and joint loading conditions during mogul skiing. It is important to assess the acceptance of the new technology by the users, namely the skiers, who are the target group for this equipment.

4.2 Aims

The four major aims of this project are:

- Aim I: To evaluate the effect of a force measurement device on skiing kinematics and skier perception as a fundamental requirement for the following investigations.
- Aim II: Verifying the data analysis system under outdoor conditions. This includes the investigation of a mogul skiing resembling movement with a boot modification, the comparison of pressure measurements inside the boot with a force measurement device and the implementation of a computer model (base line and intervention data for recreational skiers).
- Aim III: To collect data on mogul skiing techniques in order to estimate loading ranges and movement patterns as they are encountered in a mogul skiing course (base line data and intervention data of elite freestyle skiers)
- Aim IV: To assess the effect of greater ski boot flexibility in anterior direction on loading patterns and performance in freestyle skiing using biomechanical modelling techniques.

In addition to this there are several sub-goals to be achieved as this project proceeds (Figure 30).



Figure 30: Sub-goals to follow within the successive studies, their contribution to the studies and to the overall aims.

4.3 Methodological overview

This PhD project has been developed in three phases. In phase I a methodology to measure ski boot contact forces was validated. While the device's accuracy has been established within other projects via comparisons to laboratory-based equipment (Kiefmann, 2006), its influence on the athletes' performance and thus the applicability to outdoor tests was assessed (Study I).

Phase II entails the collection of data on selected freestyle related movements in order to investigate loading ranges as they are found in the freestyle skiing environment, including equipment interventions (Studies II and III).

In phase III the effects of two specific ski boot interventions on loading and performance patterns in freestyle specific movements such as mogul skiing have been assessed using mathematical modelling techniques (Studies II and III).

4.3.1 Study I

It is an essential requirement that measurement devices do not influence the athlete's performance whilst still providing precision. Therefore the first step of this project was to

determine whether the device affects the riding performance in mogul skiing. This study was conducted in Snowplanet, an indoor skiing facility in Auckland, New Zealand. A prototype of the actual force plate was used to measure changes in kinematics. In addition, the users were asked their opinion on the device with respect to skiing comfort. A previously documented perception questionnaire was used (Milani, Hennig, & Lafortune, 1997) and a Simi Motion high speed video system was employed after specific validation tests (chapter 6).

4.3.2 Study II

Testing sessions for study II were undertaken in the European Alps, Switzerland. This was done as there was easier access to more stable climatic conditions and innovative kinetic measurement equipment provided by The University of Technology Munich, Germany. This study was a pilot study verifying a comprehensive set up of both kinematic and kinetic measurements to assess the ski boot intervention with regard to loading and movement patterns. Only a lab based validation of the mobile force plate was carried out prior to data collection in the skiing environment. The plate was also compared to pressure measurements inside the boot to reveal possible differences and estimate the plausibility of previous results. Injury prevention for the knee is the focus of the current project, hence after the on mountain data collection a computer modelling software was applied to calculate possible changes to knee loading.

4.3.3 Study III

Study III was conducted on a glacier in the German alps for the same reasons as study II and used a similar set up to this study. However, several technical and logistical developments were applied have been made (Chapter 9) to allow for more specific conclusions with regard to advanced freestyle skiing. A comprehensive improved kinematic set up served for acquisition of data, which was used for model calculations as in study II. Additionally several expert evaluations have been included using the validated perception questionnaire used in study I as well as personal communications with coaches, athletes and technicians.

Chapter 5: Study one: Short term adaptation effect of a prototype force plate on kinematics and perception in mogul skiing

5.1 Introduction and purpose

To date, the majority of kinetic testing in snow sports has been conducted on traditional alpine skiing, but rarely on freestyle skiing (Friedl, 2007; Kryszohn et al., 2005). As freestyle skiing is an outdoor activity, there are major technical challenges involved and a suitable methodology for data collection is required. A newly developed and tested six-component dynamometer for measuring ground reaction forces has been presented by a German research group (Kiefmann et al., 2006). This measurement device mounted at the interface between the boot and binding was made available for the current project to be applied during the field tests. The major goal was to limit the impact of measurement units on riding performance whilst still providing precision. However, the first step should be to ensure that this holds true rather than commencing a comprehensive study and reject the data due to major impairments.

While the additional height of a measuring unit may produce a higher stance in the skier, Niessen and associates (1999) have established that the main values of both moments and forces increase only slightly, but not significantly, with a greater riser height in giant slalom. Correspondingly, slight increases in moments and forces are caused by a greater speed resulting in a decreased finishing time (Niessen et al., 1999). However, no quantitative studies have been conducted addressing kinematic changes in response to increased riser height. This information would be of value in validating the use of a rarely used interface, and consequently the applicability of a new measurement device.

The purpose of the first study was to examine the effects of using a force measurement device on the riding technique in mogul skiing. A simulated version of the device was positioned between the ski boot and binding. The current study was designed as a prerequisite for further comprehensive biomechanical research in freestyle skiing. This study has been published by the author and the text in the current chapter has been adopted to a large extent (Kurpiers, McAlpine, & Kersting, 2009).

5.2 Hypotheses

| Hypothesis I.a): | The use of the device will be perceived by the users as negatively | | | |
|------------------|--|--|--|--|
| | impacting riding performance when worn initially. However, over a | | | |
| | short time the subjects will become accustomed to the device. | | | |
| Hypothesis I.b): | Minimal effects on kinematics are expected initially, however these | | | |
| | will return to baseline values after a short familiarization period. | | | |

5.3 Methods

5.3.1 Subjects

A tentative power calculation using the G*Power 3.0.8 freeware has suggested eight participants for a statistical power of 0.8. These calculations were based on the pilot data collected in the first study of this project and thereby on the assumption of measurement variability of 10%. Previously conducted studies on the effect of equipment modifications in skiing studied between one and 21 participants (Kryszohn et al., 2005; Niessen et al., 1999; Schaff & Olbert, 1996). It was observed that the repeatability of the test runs was higher in elite mogul skiers due to their high skill level (Schaff & Olbert, 1996). Schaff (1995) revealed that inter- and intra-subject variations are minimal in elite level freestyle skiers, which would justify the decision for a smaller sample size.

All experimental procedures were given ethical approval by the University of Auckland Human Participants Ethics Committee (Ref 2007/106). All testing was undertaken at the Snow Planet indoor snow-sports facility, Silverdale, Auckland, New Zealand from 30.5. to 18.6.2007. A total of eight experienced skiers (two females, six males) participated in the study (Table 2). Prior to testing, all participants were asked to complete a questionnaire which screened for potential contraindications to the assessment protocol. This questionnaire also addressed skiing and general sporting experience in addition to the individual's equipment preferences. Only expert skiers were invited to participate in the study, in order to reduce between-trial variability. An expert was defined as the ability to successfully complete a fluent mogul skiing technique while retaining snow contact with a steady upper body, extensive leg movement and controlled, rhythmic changes in direction (FIS, 2007). Both males and females were included in the analysis as the aim of this study was to attain results that could be applied to the general freestyle-skier population.



| PARTICIPANT [N=8] | AGE [YEARS] | GENDER [M/F] | BODY HEIGHT [CM] | EXPERIENCE [YEARS] | CLASSIFICATION |
|----------------------|----------------|-----------------|------------------------|-----------------------|----------------------------------|
| P1 | 30 | М | 180 | 27 | Competitor/ Instructor |
| P2 | 31 | F | 165 | 9 | Instructor |
| P3 | 23 | F | 170 | 20 | Instructor |
| P4 | 25 | М | 183 | 21 | Competitor/ Instructor |
| P5 | 24 | М | 163 | 21 | Competitor/ Instructor/ Coach |
| P6 | 42 | М | 179 | 22 | Instructor |
| P7 | 21 | М | 171 | 19 | Competitor |
| P8 | 24 | М | 184 | 10 | Competitor/ Instructor |
| Mean | 27.5 | M=6 | 174.4 | 18.6 | Comp.=5 |
| SD | 6.78 | F=2 | 8.2 | 6.1 | Instr.=7 |
| | | | | | Coach=1 |

Table 2: Anthropometrics and experience data of samples.

5.3.2 Measurement equipment

To determine whether the device affects the riding performance in mogul skiing, a custom-made prototype of the actual force plate was used to determine the changes in kinematics, and in the subjects' perception.



Figure 31: Mock-up of force plate between ski boot and binding.

The prototype device was made of aluminium, weighed 2 kg, and was 4 cm high (

Figure 31). This simulated force plate was built in cooperation with the Institute of Bioengineering, The University of Auckland, New Zealand.

The test ski was a Head Race/Allmountain Carver type 'Super Shape' 170 cm in length and a sidecut of 121/ 66/ 106 cm leading to a radius of 12.1 m. A Tyrolia type rental binding was used to facilitate adjustments to different sole lengths between test sessions.

This equipment was provided by the main investigator.

Body motion was assessed during the runs using 3D video analysis. Table 3 displays the components required for the testing procedures.

| ITEM | AMOUNT | BRAND |
|--|--------|------------------------------------|
| High speed cameras | 4 | Basler A602f |
| Stationary computer | 1 | Simi Motion software version 266 |
| Camera cable (10 m) | 10 | |
| Hubs (to connect camera cables) | 8 | |
| Genlock adapters | 4 | |
| Calibration rod (2m) with 3 reflective markers attached (4 cm) | 1 | Custom made |
| Theodolite | 1 | Geodimeter [®] System 600 |
| Elbow screw fitting, screws and tools to mount the cameras to the brackets of the hall | 4 | |
| Skis | 1 pair | Head Super Shape |
| Racing suit with markers attached | 1 | |
| Mock-up device | 1 | Custom made |
| Power supply | | |

| Table 3: | Items | required | l for | testing. |
|----------|-------|----------|-------|----------|
| | | | | |

5.3.3 Kinematic setup

A four-camera motion high-speed video system (MHSVS) mounted to the walls of the building collected video footage at 100 Hz (Simi Motion, Unterschleissheim, Germany). The upper cameras were positioned in approximately 60 degrees to the lower cameras for video an image size of approximately 10 m \times 3 m (Figure 32).



Figure 32: Schematic of camera setup.

A set of 42 black markers were fixed to the skier bilaterally on the bony landmarks, to define the shank, thigh, arms and trunk segments. Table 4 lists the exact body parts used for marker attachment including the marker names and body segment. These were affixed with adhesive tape on a white racing suit worn by the subject. The list also includes additional points that were markerless such as the bottom of the poles or the head centre, which summed to a total of 45 digitised points, including eight static markers or points respectively.

| BODY SEGMENT | MARKER NAME | LOCATION |
|--------------|-------------|--------------------------------------|
| Head | HEAD | Cranium |
| Trunk | UPBREAST | Manubrium Sterni |
| | LOBREAST | Processus Xiphoideus |
| Right arm | RSHO | Caput Humeri right |
| | RELBC | Articulatio Cubiti right |
| | RWRC | Articulatio Manus right |
| Left arm | LSHO | Caput Humeri left |
| | LELBC | Articulatio Cubiti left |
| | LWRC | Articulatio Manus left |
| Hip | RASI | Right anterior superior iliac spine |
| | LASI | Left anterior superior iliac spine |
| | RPSI | Right posterior superior iliac spine |
| | LPSI | Left posterior superior iliac spine |
| | | |

Table 4: List of markers

| BODY SEGMENT | MARKER NAME | LOCATION |
|-------------------|--------------------------|-------------------------------------|
| | RTROCH | Trochanter maior right |
| | LTROCH | Trochanter maior left |
| Right thigh | RTHIPROX | Right quadriceps proximal |
| | RTHIDIST | Right quadriceps distal |
| Left thigh | LTHIPROX | Left quadriceps proximal |
| | LTHIDIST | Left quadriceps distal |
| Right knee | RKNELAT | Lateral epicondyle of femur |
| | RKNEMED (static) | Medial epicondyle of femur (static) |
| Left knee | LKNELAT | Lateral epicondyle of femur |
| | LKNEMED (static) | Medial epicondyle of femur (static) |
| Right shank | RTIB | Medial to tibia |
| Left shank | LTIB | Medial to tibia |
| Right Foot | RTOE | 2 nd phalanges distales |
| | RHEE | Posterior to calcaneus |
| | RANKLAT | Lateral malleolus |
| | RANKMED (static) | Medial malleolus (static) |
| Left Foot | LTOE | 2 nd phalanges distales |
| | LHEE | Posterior to calcaneus |
| | LANKLAT | Lateral malleolus |
| | LANKMED (static) | Medial malleolus (static) |
| Equipment markers | RUPPOLE | Right upper pole |
| | RLOPOLE | Right lower pole |
| | RTIP | Right ski tip |
| | RTAIL | Right ski tail |
| | RFRONTBIN (static) | Right front binding |
| | RREARBIN (static) | Right rear binding |
| | LUPPOLE | Left upper pole |
| | LLOPOLE | Left lowe pole |
| | LTIP | Left ski tip |
| | LTAIL | Left ski tail |
| | LFRONTBIN (static) | Left front binding |
| | LREARBIN (static) | Left rear binding |

5.3.4 Perception

After the first and the final recorded mock-up run, the skiers filled out a second questionnaire about perception of their performance compared to the runs with normal equipment, to ascertain the extent to which they had become accustomed to the device. The items retrieved from the perception questionnaire related to safety, stability on the ski, speed control, effects on skiing movements such as edging (horizontal movement left/right), absorbing (vertical movement, bending/ straightening legs), forward/ backward leaning and overall perception. The questionnaire was set up as a rating scale to circle a number from 1 to 9 where1 was defined as the worst possible perception and 9 was

defined as the best possible perception compared to the runs without the device. The run without the device was rated the number 5 on the questionnaire and therefore states 'no difference' as circled by a participant (Appendix 4, Figure 36).

5.3.5 Kinematic calibration

A Total Station (Geodimeter® System 600, Sweden; accuracy \pm 5mm) was employed for the calibration of the image of the recordings. This device was used to survey three retroreflective markers placed on a pole of 2m length (Figure 33). A short video was recorded simultaneously. This procedure was repeated with the pole located in 12 different positions within the image of recordings resulting in a total of 12 videos and 36 points. A still image was exported from each video clip as a BMP file and therefore there were 12 images for each camera. A MATLAB script was used to combine these into a new video file which was subsequently loaded into the Simi Motion software System. A calibration file was created from the coordinates measured with the Total Station and was imported as the calibration settings. Marker one was defined as the origin (0,0,0) and all other points were altered accordingly. The volume of interest was calibrated on each testing day. The 36 control points were manually digitised. This calibration procedure has been validated in a previous study (Darlow, 2007).



Figure 33: Calibration of reference points using a Total Station.

5.3.6 Testing procedure

Test sessions comprised of a series of twelve runs down a mogul course of 2.5 m by 25 m, with an inclination of approximately 15 degrees and a distance of 4 m between each mogul. The mogul course consisted of eight moguls, but mogul number five and six were

the relevant moguls for this data acquisition to ensure that all participants had enough time to create their velocity and rhythm. The temperature was kept at a constant -5°C and as testing was indoors and within a fenced area, the conditions were constant for all test sessions.

All subjects had the opportunity to warm-up, as required, on the normal slope and six runs on the mogul course, with the instruction to exercise correct mogul technique. They were filmed for three consecutive runs with their normal equipment. Subsequently, the mock-up was applied and the first run was recorded. Following this, another five mogul runs with the device were used for practise. Subjects then completed three more filmed runs wearing the device.

The whole procedure for the testing sessions is summarised in Figure 34.





5.3.7 Data analysis

Parameters analysed were three dimensional knee angles of the inside and outside leg, forward lean of the trunk with respect to the hip, and the sideways and forward inclination of the hip in the reference system. Further, the path of the body's CoM was determined using anthropometric tables from Dempster (1959) and the horizontal distance of the CoM and a points halfway between both ankle joint centres were measured. Data were processed off-line using Simi Motion Software. The files with tracked three dimensional trajectories were copied to Motion Analysis Eva 321 which calculated the virtual joint

centres for the shoulders, hips, knees and ankles. Subsequently, data were processed using MATLAB (Mathworks, USA) to calculate the joint angles and correlations to the path of the centre of mass with a straight line connecting the moguls. Figure 35 contains a graphical presentation of the investigated kinematic parameters.



Figure 35: [modified from Kassat (2000)]: Graphical illustration of kinematic parameters investigated (KA = knee angle, TA = forward lean of the trunk, HA = forward tilt of the hip, CoMdir = path of the body's centre of mass, CoMdist = horizontal distance of CoM and a point half way between both ankle joint centres).

5.3.8 Statistics

The mean values and standard deviations (*SD*) were tested for normality applying a Kolmogorov-Smirnov test and symmetry prior to group comparisons. If normality was rejected, a Wilcoxon test was used. Otherwise, a repeated measures ANOVA was employed to test for differences in perception and kinematic measures using a Student Newman-Keuls test for post hoc comparison. Significance was tested at < 0.05. All data were statistically analysed using SPSS 15.0.

5.4 Results

Perception ratings showed no significant detrimental changes following the familiarisation period. However, "Safety" rating was reduced when using the equipment for the first time, but significantly improved over the familiarisation runs. For the factor "Edging" the

subjects rated both the first and the final run significantly higher than the normal runs. The most frequent limitation of the device, commented by the subjects, was its weight which initially reduced agility and an aggressive forward lean was difficult to maintain. In Figure 36 the mean values and SD for the seven ratings regarding the skiers' perception of their performance are displayed.



Figure 36: Perception after ninth mock-up run (negative values = worse, 5 = no difference, positive values = better compared to ordinary equipment; * = significant change based on p < 0.05).

Kinematic analysis revealed no significant differences. Table 5 displays the mean values of the assessed kinematic parameters, with standard deviations, for the three relevant runs. Knee angles ranged from 77° to 156° degrees. The average knee flexion on the inside legs (IKnee) was greater than on the outside legs (OKnee). Furthermore, the range of motion for knee flexion and extension in the first mock-up run was noticeably but not significantly smaller than in the normal and in the familiarised run (Figure 37, Table 5).

| | normal | | initial | | familiarised | |
|-------------------------------|--------|---------|---------|---------|--------------|---------|
| Parameters | Mean | St.Dev. | Mean | St.Dev. | Mean | St.Dev. |
| InsideKneeFlexionMax [deg] | 93 | 5 | 101 | 12 | 91 | 9 |
| InsideKneeExtensionMax [deg] | 135 | 10 | 133 | 11 | 131 | 11 |
| OutsideKneeFlexionMax [deg] | 96 | 9 | 106 | 8 | 94 | 9 |
| OutsideKneeExtensionMax [deg] | 137 | 11 | 142 | 10 | 135 | 6 |
| SideFlexHipMin [deg] | -20 | 6 | -19 | 4 | -18 | 4 |
| SideFlexHipMax [deg] | -3 | 8 | -1 | 6 | 1 | 7 |
| FrontFlexHipSt [deg] | 29 | 11 | 30 | 8 | 28 | 10 |
| FrontFlexHipF [deg] | 29 | 7 | 25 | 11 | 22 | 10 |
| FrontFlexHipMin [deg] | 4 | 10 | 1 | 8 | 2 | 9 |
| FrontTiltTrunkSt [deg] | -10 | 4 | -11 | 4 | -11 | 4 |
| FrontTiltTrunkF [deg] | -12 | 3 | -16 | 5 | -13 | 4 |
| FrontTiltTrunkMax. [deg] | -5 | 2 | -6 | 3 | -6 | 3 |
| CoM_foot [mm] | 323 | 59 | 280 | 77 | 261 | 71 |

Table 5: Mean values and standard deviations of kinematic parameters for the three relevant runs (St = at Start, F = at Finish, Min = Minimum, Max = Maximum, CoM = Centre of Mass, CoM_foot = horizontal distance between CoM and a point half way between both ankle joint centres)

For the hips and upper body, several parameters were calculated which may be used to characterise forward leaning of the skier. Lateral flexion of the upper trunk against the hip segment (SideFlex) on average showed a flexion away from the turning direction as would be expected in parallel turns. The front flexion of the upper trunk against the hip segment was similar at the start and end of the turn, i.e., on top of the moguls, and straighter in the dip between moguls indicated by a smaller angle (Table 5). The values describing the orientation of the hip in the global coordinate system show similar values at start and finish, indicating that body position is consistent across the trials in the measurement area. Forward inclination of the hip is less negative when going through the dip, indicating a more upright posture according to a combined knee and hip extension in this phase. The sideways movement of the hip shows almost exclusively negative values, indicating a slight left tilt compared with the standing trial.



Figure 37: Mean values and SD of inside and outside knee angle for three runs for one turn.

All these parameters show minor alterations and remain the same over the three runs. The forward distance of the centre of mass to a point half way between the ankle joint centres varies slightly; 26 cm in the familiarized mock-up run and 32 cm in the normal run. The lateral correlation of the centre of mass relative to the connecting line between mogul one; between 0.92 in the initial mock-up run and 0.97 for the familiarized mock-up run which was non-significant change.

5.5 Discussion

The present study aimed at identifying the effects of introducing a prototype force sensor on kinematics and the skiers' perception to mogul skiing. Three dimensional video analyses and perception questionnaires were applied to eight experienced skiers for skiing over an indoor mogul course with standard equipment and measurement devices. Results demonstrate that there are no significant alterations in the skiing technique. Perception of edging and safety altered when introducing the mock-up. The edging improvement persisted while a reduced safety rating returned to normal after a familiarization period of five runs.

It is conceivable that subjects skied more cautiously the first time when using the mock-up device reflecting in changes of knee flexion and extension as shown in Table 5 and Figure 37. This matches their comments on the questionnaire where most of the subjects stated feeling less confident due to, primarily, the added weight. However, after five

customisation runs the safety was returned to normal values, supported by the greater range of motion in the knee angle in the familiarized mock-up run (Figure 37) and the safety indication in the perception chart (Figure 36). This observation suggests a return to a more agile mogul skiing technique even though the difference was not significant.

The results demonstrated that the higher stance on the skis and the added weight due to the measurement device can initially change the skiers' perception of their performance. Niessen and associates (1999) found that a greater riser height increased the speed. Hence, it could be expected that a skier should become accustomed to this change of geometry and perceives their riding technique slightly differently when compared to the runs with a lower riser. However, the analysis of the final runs in this study represents a reasonably fast customization and all components showed a trend of improvement from the first to the last run, thus suggesting familiarisation was achieved.

Despite this, there are no investigations published regarding the changes in movement patterns due to a higher stance on the ski. In addition, the mogul skiing technique differs from traditional skiing and carving turns, respectively, which entails specific aspects to consider such as vertical agility of the legs, fast changes of direction and the high challenge of maintaining stability at a fast pace. This was covered by the questionnaire in the current study. The parameters examined by Niessen and colleagues (1999) were the finishing time, forces and moments relative to riser height. They detected that binding plates up to 2 cm in carving turns do not increase the forces and moments. This is in agreement with the results in the current study although different parameters were investigated.

The higher stance on the skis did not produce any significant differences in the kinematic variables within the turn. However, minor changes in knee angles and the path of the centre of mass were observed in the initial mock-up run due to, possibly, a more deliberate riding style, but not after familiarization. In addition, Niessen et al. noted that the boot-snow contact decreases at high edging angles and potentially reduces the risk of falling (Niessen et al., 1999). This might hold true for the intended applications in moguls as well, thus possibly even being of benefit. On the other hand, guidelines are suggesting quick edge changes as a requirement for mogul skiing (DVS, 2002), therefore it could also be a trade-off between added weight and geometry.

These interpretations are subject to certain limitations. The sample size used in this study was relatively small. There was an attempt to keep the height of the moguls consistent which was only possible to a certain degree. This is because snow continuously piled off the downhill sides of the bumps to the uphill side as commonly occurs in mogul skiing (D. Bahr, 2006). The recorded trials were manually digitised since an automatic tracking function did not function due to poor light conditions in the ski hall. Despite these limitations, the findings of this investigation are of particular importance for follow-up studies in skiing using this specific measurement device. Since there are technical challenges involved in the skiing environment, researchers need to utilize reliable measurements. Accordingly, the skier's natural movement must not be seriously altered by the measurement device. These are two contradictory requirements and a compromise is difficult (E. Muller & Schwameder, 2003a). An inherent challenge with these measurement systems is the trade-off between accuracy, and impairment of the athlete's performance. It is the primary aim to minimize the size of the device, whilst still improving precision. Consequently, the present results justify the prospective utilization of the new measurement system and provide the framework for follow up studies in freestyle skiing.

5.6 Conclusion

The chosen dimensions of the modified measurement unit did not have significant effects on the riding technique of the skier. Therefore, it is possible to further utilise the functional force plate presented by Kiefmann et al. (2006) for future studies in freestyle skiing. The use of this will provide the framework for future studies on injury research, performance- and equipment-related studies providing athletes, coaches and consumers with valuable information.

In order to provide reliable kinematic data and improve the marker set prior to further applications in the field, the measurement system, the procedures and the extent of possible marker movement need to be validated in a laboratory based environment as accomplished by the following sub-study.

Chapter 6: Validation of the kinematic measurements

This study validates the measurement equipment utilized for the studies and its accuracy. Kinematic data often serve as the input for computer simulations. Thus, a high level of measurement accuracy is required in order to assess technique or injury mechanisms in snow sports in certain situations or following equipment interventions. However, some imprecision must be accepted as measurement errors are inevitable. For instance, a standard resolution of 768 by 576 and an image of recording of 10 m leads to a pixel length of 1.3 cm (Blumenbach, 2005). Accordingly, the joints of a calf of 50 cm length show a distance of 38 pixels to each other. Digitisation of both end points result in a theoretical standard deviation of $\sqrt{2*1.3}$ cm=1.8 cm, which corresponds with a relative measurement error of 4% of the segment length (Arndt, Brüggemann, Virmavirta, & Komi, 1995). Hence, adjustments for kinematic data acquisition need to be optimal, which is highly challenging under ski field conditions. Thus methodological validation is required to ensure the best possible accuracy of any results obtained.

Little work has investigated the validation of kinematic parameters in the field of snow sports (Darlow, 2007; Klous, Schwameder, & Mueller, 2006a; Schwirtz, Boesl, Hartung, & Huber, 2006). Therefore, the current sub-study focused on the validation of a mobile high speed video system (MHSVS) and motion capture procedures for field studies in snow sports.

6.1 Methods

This study consisted of two parts, 1) a laboratory-based validation of system precision and 2) the investigation of a possible difference in precision between skin-based markers (condition SB) versus markers attached to a racing suit (condition RS).

This testing session took place in the Biomechanics laboratory of The University of Auckland, New Zealand. Two participants, free of neuromusculoskeletal injury, wore a racing suit with 19 reflective markers with a diameter of 40 mm attached on the bony landmarks (Figure 38). The MHSVS (Simi Motion, Germany) was set up with four cameras recording at 100 Hz and a resolution of 656 by 490 pixels with an angle of greater than 60 degrees of any two optical axes and a distance of five meters from the participant. A Vicon-MX (Vicon Motion Systems Inc., UK) system was set up for comparison with 8 infrared cameras recording at the same frequency of 100 Hz.

Lower Body Marker Set Snow Sports 23 Markers (4 static only)

15 body

8 boot

ASIS PSIS Xiphoideus Lateral Knee Medial Knee (static) Tibia Thigh (2*each) Ankle Lateral Ankle Medial (static) Heel Toe

BOTH SIDES

Figure 38: Snow Sports marker set (ASIS = anterior superior iliac spine; PSIS = posterior superior iliac spine).

Both camera systems were calibrated using the same calibration cube. The touch down of a dropped marker was regarded as the reference frame for synchronisation of the systems. For part I, static standing trials were collected with the RS before specific movement trials. The analysis protocol included the identification of inter-marker distances (Figure 38). After the first upright static trial (UST), participants remained in a position with a 90° and 45° knee angle for an additional two static recordings. For the dynamic trials (DT), participants performed 10 squat jumps with slight twists, rotating the body position 45° to the sides during each jump in line with marks on the floor. This simulated a realistic range of movement and movement speed that complies with a field testing situation in freestyle skiing (Mustonen, 2007). For comparison of the two systems the trajectories of all points were measured by both systems and compared. Therefore the automatic tracking function was used which pinpoints the middle of the marker automatically for digitisation. This included knee joint centre position (KJCPos) and ankle joint centre position (AJCPos). Following this, both the postures with pre-determined knee angles and the UST were recorded again in order to allow for evaluation of marker movement during specific body movements and sustained changes in marker distances at rest. Each participant repeated this procedure twice within the session. After three trials both participants repeated the same procedure in the SB-condition for part II in order to identify possible differences in marker distances during both static and dynamic trials (condition RS vs. SB).

Descriptive statistics were employed to show the between-trial variability within the sessions for each inter-marker distance by using the averages and standard deviations from the Microsoft Excel Software. The Bland Altman plots were used to illustrate the comparison between the systems.

6.2 Results

The KJCPos deviated about 3 mm in a positive and 4 mm in a negative direction with respect to the vertical axis (Figure 39). The AJCPos showed a greater range of deviation with up to 18 mm.



Figure 39: Comparison of automatic tracking Vicon vs. Simi, a) knee joint centre, b) distribution of standard deviation

The measured differences between the markers in the RS condition varied 28 mm between the knee and the trochanter and 20 mm between the knee and the ankle during the squatting task. The difference between joint markers such as the knee or the ankle and non joint markers such as the tibia or the thigh remained with 4-6 mm variability relatively constant (Figure 40).



Figure 40: Change in distance between left trochanter marker and knee marker during squatting task in RC condition.

The measured differences between the markers in the SB condition varied about 47 mm between the knee and the trochanter and 35 mm between the knee and the ankle during the squatting movement (Table 6). Joint markers versus non-joint markers showed a variability of about 21 mm.

The distance between the markers in the UST and the pre-determined 45° and 90° knee angle position varied slightly from the first to the second trial with a 1-5 mm difference, but not from the second to the third trial (1 to max. 3 mm variability). The marker distances in the SB condition varied constantly between 2-5 mm during all static trials depending on the marker combination.

All data were processed by two persons and the mean values served as the illustrated results (Table 6).

| Dynamic | | knee-troch | knee-ankle | knee-tib |
|---------|-------|------------|------------|----------|
| SB | Max | 442 | 433 | 208 |
| | Min | 395 | 398 | 187 |
| | Range | 47 | 35 | 21 |
| | | | | |
| RS | Max | 449 | 452 | 178 |
| | Min | 419 | 430 | 171 |
| | Range | 30 | 22 | 7 |
| Static | | 1st to 2nd | 2nd to 3rd | |
| SB | UST | 2 | 2 | |
| | 45° | 4 | 3 | |
| | 90° | 2 | 1 | |
| RS | UST | 5 | 1 | |
| 110 | 45° | 3 | 1 | |
| | 4J | 5 | 5 | |
| | 90° | 2 | 1 | |

Table 6: Differences between mean values for marker distances for the dynamic and static trials (knee-troch=knee- trochanter, knee-tib=knee-tibia, SB=skin based marker, RS=race suit marker).

6.3 Discussion

Results demonstrate a high precision of the Simi Motion system and a reasonably acceptable marker movement on the race suit compared to skin based markers.

The Vicon system is deemed to be the 'Gold Standard' with a precision of approximately 2 mm (Dempsey et al., 2007). The Simi Motion Software's accuracy depends on several parameters that need to be systematically analysed. The differences in resolution of both systems should be considered as an influencing factor.

Klous and associates (2007; 2006b; 2006), for their methodological experiments, used a five camera set up for kinematic data collection at 50 Hz, which was accurate with error margins of one to two cm on a measuring image of 20 m. Square tapes of 2.5 cm by 2.5 cm were used as markers. Briggs et al (2003)reported mean absolute error values of 7 mm for calculated distance measured by a Simi Motion system. These results comply with the current study based on values gained in the laboratory environment.

Skin markers are deemed to represent the skeletal knee joint motion regarding flexion and extension. However, according to Reinschmidt et al.(1997) internal-external rotation and adduction-abduction display larger errors using skin markers during running. Alexander & Andriacchi (2001) and Capozzo et al (1996) showed a skin based marker movement of up to 40 mm during performance. However, skin based markers are considered the most

reliable, and are used as the reference in this study. Several studies have used bone pin markers and derived marker trajectories to verify soft tissue movement during walking. It has been noted that skin movement artifacts vary across subjects (Benoit et al., 2007). Holden (1997) measured errors for maximum translation of about 13 mm and rotational errors of up to 8° around the calf's longitudinal axis. These changes in kinematics caused kinetic changes of 9 Nm in knee joint abduction-adduction moment and up to 39 N for medio-lateral knee forces. Other studies reported maximum rotational errors of 4° at the calf which elicited errors of 4 Nm in the abduction-adducton moment (Manal, McClay, Richards, Galinat, & Stanhope, 2002). The utilisation of bone pin markers, however, is not feasible for snow sports.

Due to safety issues, skin markers are impossible to use in the ski field. Hence, markers attached to clothing are necessary and the resulting limitations due to marker movement must be tolerated. In the current study, the race suit based markers show the most obvious marker movement between two joint markers such as the knee and the trochanter during the squatting task. However, the variability of marker distances between the second and third static trial including pre-determined squat positions are negligible. This suggests after the first movements the racing suit fits more appropriately around the body. This information shows that all markers should be readjusted or attached following a warm up to improve precision. The marker movement of the skin based and race suit based markers was identical following the first dynamic trial for all static trials.

The RS condition seems to show less marker movement than the SB condition. However, as can be assumed the RS condition is likely to have greater marker movement. The markers on the skin are assumed to move relatively accurately with the skin except the known reported errors due to wobble effects. In contrast, the race suit is malleable and moves with the skin. The SB condition showed 15-20 mm greater marker movement compared to the RS condition. Therefore a reduced marker movement in the RS condition can be deceptive, because it should be considered that the RS markers move slightly with the race suit even though the distance does not vary as much as in the SB condition. Thus it is expected that, opposed to common belief, less marker movement as shown for the RS condition needs to be interpreted as an indicator for slightly less precision in the measurements. However, considering the need for attire in snow sport field tests and the relative similarity of the results, the utilisation of markers on a race suit appeared to be applicable and recommendable for outdoor applications in snow sports.

Chapter 7: Model development and verifications

Study II and III of the current project describe a comprehensive set of equipment and methods including high speed cameras and calibration techniques as presented within study I. This chapter contains an outline of the kinetic measurement, a ski boot stiffness test and an introduction of a specific computer modelling approach. Furthermore, previous validations of the original model that the current model is based on will be briefly presented as well as a sensitivity analysis of the current modelling application.

7.1 Kinetic measurement

7.1.1 Ski force plate design

The six-component dynamometer for measuring ground reaction forces is made of aluminium, weighs 2 kg and is 36 mm high \times 62 mm wide. It consists of three different parts, specifically the boot sole adapter, the load cell and the binding adapter (Figure 41). The ski boot is attached to the adapter with a buckle. The load cell is situated between the other two parts and contains six one-dimensional force sensors and a mechanical uncoupling device. Transducer elements are designed as shear beams instrumented with strain gauges. Due to the specifically defined positions of the sensors, it is possible to calculate all moments (M_x, M_y and M_z) and pinpoint the centre of force in the x/y-plane, using specific equations (Equation 1).

Equation 1: Conversion of sensor signals into forces and moments.

$$\begin{cases} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{cases} = \begin{bmatrix} C \end{bmatrix} \begin{cases} X \\ Y_1 \\ Y_2 \\ Z_1 \\ Z_2 \\ Z_3 \end{cases}$$

C is the calibration factor for the conversion of the recorded signal into the acting forces. The factors of the first three rows are N/mV and convert the sensor signals into the forces F_x , F_y and F_z . Rows four to six are Nm/mV and convert the sensor signals into the moments M_x , M_y and M_z .

The device has an external power supply for the gauges and a data logger (miniature computer) is connected to the device in order to transfer collected data for further
processing. The binding adapter, as the third part of the system, is adjustable in length from 290 to 390 mm and clicks the whole system on the binding (Kiefmann et al., 2006). The coordinate system of the dynamometers was defined x-direction; anteroposterior (alongside the ski), y-direction; medio-lateral (across the ski) and the z- axis vertical relative to the ski. The midpoint of the sensor assembly was the origin.





7.1.2 Ski force plate accuracy

A laboratory-based validation study has been conducted by German collaborators to assess the accuracy of the calibration matrix. Two different performance testing rounds were conducted, each followed by design improvements and modifications. The first test was a static load assessment to provide information about the capability of the device as well as support for the design and data processing refinements prior to on-snow field testing. For the second testing session dynamic loads of different magnitudes and directions were applied to examine the device's accuracy under relevant conditions to those encountered in the field tests (Figure 42). An algorithm was programmed using MATLAB software to enable the calculation of the calibration factors from raw data. This procedure aimed at using the calibration matrix to derive the sensor signals to the actual loads. Figure 42 displays one of the components measured by the ski force plate in comparison to a floor mounted Kistler force plate as a reference in the laboratory environment.





Figure 42: Comparison of lateral torque (Mx) from Kistler force plate (black, unfiltered signal) and ski force plate (purple) (Kiefmann, 2006).

The lateral force F_y and the longitudinal moment M_z showed minor inconsistencies (Kiefmann et al., 2006) The overall accuracy was ± 4 N and ± 0.1 Nm, which is within the acceptable range for force plate errors of GRF < 2° as indicated by Lewis (2007).

7.2 Ski boot stiffness tests

This study has been conducted to quantify the respective two experiments of study II and study III. In order to assess the effect of modified ski boots on knee joint loading, the stiffness of the two different ski boot models are required to compare these properties. The measured values are also important for input into the subsequent computer simulation. For this test a custom made prosthetic leg as a boot stiffness testing device has been constructed, as briefly described in the following sub chapter.

7.2.1 Stiffness testing device

A foot with size US 9 was used to replicate an artificial foot and leg according to its dimensions. This size was assumed to fit in all three different sizes of ski boots (28.0, 28.5, 29.0) which was comparable to the size of US 9 to 10. The real leg was covered up to five cm distal to the patella by plaster in an unloaded condition to mimic stepping into the boot. This resulted in a negative cast which was cut into two parts, the foot and the leg. The negative cast was split about a transverse axis at the tip of the lateral malleolus and slightly below the level of the medial malleolus.



Figure 43: Positive cast of the foot and the lower leg.

The negative cast was used to build a positive cast as an artificial leg by filling both parts with plaster (Figure 43). The toe area of the model foot was removed to allow ease of entry into the boot. To resist the forces created in the experiment, the outer layer of the artificial leg was made from plastic. This was accomplished by 1) warming up the plastic and 2) fitting the soft plastic around the cast. Two aluminium rods were used as ankle joints acting as levers on either side of the joint. One of these aluminium rods was longer than the other so to simulate the tibia. Sealant foam was used to fill the plastic and was covered by duct tape. The two-joint mechanism was constructed out of aluminium and delrin and resembled the axes orientations from Inman

Furthermore, the testing setup consisted of the respective ski boots clicked into a ski binding, a single axis force transducer (AST GmbH, Wolnzach, Germany) with an accuracy of 0.3 N, two ropes, a set of reflective markers (25 mm) and a Qualisys Track Manager (QTM) motion capture system (Gothenburg, Sweden).

7.2.2 Method

The prosthetic leg was put into the boot, which was buckled with the identical adjustments for all trials and all boots to ensure consistency in both conditions. The force transducer was positioned between two ropes. The end of one rope was attached to the top of the prosthetic leg and the end of the other rope was used to pull over the edge of a table as a deviation point for constant force application (Figure 44).



Figure 44: Ski boot stiffness testing setup.

A set of eight markers were attached at the deviation point, top of the prosthesis, heel of the boot, toe of the boot, upper end of the rear shaft and pivot point of the prosthetic leg. The load was applied by pulling the rope with the force transducer attached between both ropes sampled at 100 Hz using (Mr. Kick, by Knud Larsen). The applied load, the displacement of the top of the prosthesis as well as the moment arm of the load with respect to the ankle joint centre were measured (Figure 45). Maximum force and the minimum ankle angle were of focus.

All three pairs of modified boots and one conventional pair of the same model were tested three times by applying tensile loads to the leg in anterior direction and three times in posterior direction about the tibial axis. The mean values are displayed in Figure 46 and Figure 47. The movement of the tibia model in the ski boot and the force required was tested. Hence it should be noted that it was tested how the boot affects the stiffness of the ankle joint rather than the stiffness of the boot itself. Thus, the values from this sub study can not be compared to the values indicated for ski boot stiffness by companies as they solely measure material properties. The tip of the rod simulating the tibia as the lever to the ankle joint was pulled and displaced. The load was applied from an approximately perpendicular direction to the tibial rod of the prosthetic leg. The displacement of the artificial tibia, the distances and angles between the tip of the rod, the deviation point and the ankle joint centre were measured using trigonometric functions. The applied moment was plotted against the bending angle graph for all trials. The extension of the slopes was defined both negatively and positively using cubic polynomial regressions for the moments and displacements in both the anterior and posterior direction respectively. The boot stiffness is commonly measured in Newtons per degree (Bürkner & Simmen, 2008). However, the 'Anybody software' utilised later on in this project uses Newton per radian, thus the results are presented in these units accordingly.



Figure 45: Schematic of ski boot stiffness testing.

7.2.3 Results

Figure 46 and Figure 47 show the plots of the shaft elongations in the transversal plane. For a change in the angle of the flexible boot shaft of approximately 0.4 radian, an average moment of approximately 40 Nm was required. For the same displacement of the normal boot shaft, a load of 60 Nm was required. In turn, since the graphs have almost linear slopes the modified boot shaft allowed 1.6 times more flexion in anterior direction for the same applied load to the prosthesis. In the posterior direction the stiffness showed no differences between the two conditions.



Figure 46: Applied moment plotted against the bending angle of the boot for three modified boots in both anterior and posterior direction.



Figure 47: Applied moment plotted against the bending angle of the boot for the conventional boot of the same model in both anterior and posterior direction.

7.2.4 Conclusions

The results of these ski boot stiffness tests show a notably greater ankle joint flexibility in anterior direction using the modified boot. The normal boot turned out to be 160% stiffer with 46 Nm at 0.3 rad. As expected the stiffness in posterior direction showed no differences between the two conditions as no boot properties have been changed towards that direction. The calculated ankle stiffness for both conditions have been included in the 'Anybody model' as an angle-dependent resisting moment at the ankle joint.

The limitations of this test were that ski boots are commonly used in temperatures below zero degrees. This is expected to have an influence on the equipment's functionality and stiffness (Walkhoff & Bauman, 1987). Thus, it is unknown whether the boots' stiffness properties in the lab (at 20 degrees) differ from its properties in a skiing environment

where stiffness becomes relevant. Despite this as these testing conditions were standardised for all boots the differences obtained here were considered realistic.

7.3 Anybody Modeling System

The current project was focused on knee joint loading in freestyle mogul skiing comparing two different ski boot conditions in study II and study III respectively. Data collected in studies II and III will serve as the input for the inverse dynamics using the Anybody Modeling SoftwareTM. This will be briefly introduced within the following sub sections including the implementation of the model for the current application. Since an existing full body model has been modified, the model will not be explained in depth. However, references will be provided for further in depth information of the original model development.

7.3.1 Introduction

The Anybody Modeling System[™] (created at the Institute of Mechanical Engineering at the Aalborg University, Denmark) models the biomechanics of the human body as a rigidbody system, working in conjunction with its environment (Damsgaard & al., 2006). The musculoskeletal system of the human is unique and mechanically complex. To investigate this complex system using computer modeling software, the system must be markedly simplified whilst still providing a realistic representation of the moving human body. The human body contains over 650 muscles that in most instances must be divided into several mechanical units. Each muscle needs to be characterized by different parameters influencing strength, force-velocity and force-length relationships, parallel and serial elasticity, pennation angle, fiber length, origin and insertion. Other body elements such as 206 bones, joints and connective tissues such as tendons and ligaments must be represented and all these parameters slightly differ between individuals (Anybody, 2008). Therefore, a full body model requires thousands of parameters to simulate realistic human body behaviour and still does not account for sensory motor interaction abilities, visual, vestibular and somatosensory systems or tension receptors within the musculature. Thus, an adequate mechanical model as well as a suitable method for muscle recruitment is required. This will be adressed within the next sub chapters.

The Anybody system is characterized by using an inverse dynamics optimization technique to solve the muscle recruitment problem and reverses this by means of other optimization techniques so that forward dynamics problems can also be addressed. Models in Anybody work with text based input and are developed in the body modeling language 'AnyScript'. Anybody models aim to predict muscle, ligament and joint reaction forces for a given movement (Anybody, 2009a). The full body model that has been modified for this work is part of the model repository library which is publicly accessible at www.anybody.aau.dk.

7.3.2 Mechanical Model

Generally, musculoskeletal models can be divided into two groups, forward or direct dynamics models and inverse dynamic models, as mentioned in chapter 3.3 (Zajac & Winters, 1990). Both methods join kinematics and kinetics. For the forward dynamics approach, independent coordinates and the Lagrange equations are used to derive the dynamic behaviour of multi-body systems to, in turn, receive the equations of motion regarding these coordinates. Formerly forward dynamics approaches in mogul skiing simulations did not consider the snow friction as a major limitation which altered body position throughout the simulation (Friedl, 2007). Hence, conclusions with regards to the effect of ski boot shaft stiffness on joint loading in mogul skiing are not possible using this simulation technique. The computation of a complicated system such as the human body is challenging and it is difficult to keep the context of the equations well-arranged. For this reason, the forward dynamics technique is problematic.

For the inverse dynamics approach the Newton Euler equations of motion for a rigid body and the constraint equations describing the optimal joints between the bodies are used to derive the dynamic behaviour of multi-body systems. Since this leads to a complex mixture of both differential and algebraic equations, numerical integration schemes are required (Schwab, 1998).

In the Anybody software, the body is both kinematically and statically indeterminate. Therefore it has more joints than necessary to gain most common body positions and more muscles to balance than strictly necessary to balance most loading conditions. As the model is statically indeterminate it can use infinite solutions for musculoskeletal simulation problems, however, the central nervous system (CNS) is able to identify an almost ideal solution for any movement or loading. A fundamental assumption of the model is that the CNS recruits the muscles optimally according to rational criteria. More details about these criteria can be found in the literature (Crowninshield & Brand, 1981; Herzog, 1987; Pedotti, Krishnan, & Stark, 1978; Röhrle, Scholten, Sigolotto, Sollbach, &

Kellner, 1984). Thus, for a good prediction of the muscle forces it is crucial to implement a mechanical model of the musculoskeletal system including a reliable and efficient optimization algorithm to determine the muscle recruitment (Dendorfer & Toerholm, 2008). Anybody adopted a general multibody system dynamics approach using a set of Cartesian coordinates for each body. The kinematical analysis is carried out by means of Cartesian coordinates by solving a set of imposed kinematical constraints as reported by Darmsgaard et al (2006).

The Anybody Modelling System[™] is equipped with inverse dynamics tools (Figure 48) and thus the current work will be focused on this technique.



Figure 48: Schematic overview of the inversion of inverse dynamics ((De Zee, Christensen, Damsgaard, & Rasmussen, 2002).

7.3.3 Muscle Recruitment

The inverse dynamics approach has some complications such as some of the muscles involved span several joints and can be working antagonistically. Furthermore, some of the muscles are in very close proximity to bones on their way from the origin to insertion, i.e. the muscle path is not easy to predict and the muscle provides force to the bone at not only the origin and insertion points (Anybody, 2009b). The muscle recruitment concept of the human body by the CNS is very complex since there are usually more muscles involved in a movement than necessarily required to drive the degrees of freedom of the system (Damsgaard & al., 2006). This is commonly referred to as the redundancy problem of muscle recruitment, i.e. the equilibrium condition has more unknowns than it has equations. Thus, some assumptions are required in the Anybody modeling software to solve these redundancy problems.

There are different kinds of muscle recruitment criteria with respective advantages and limitations (M. S. Andersen, Damsgaard, & Rasmussen, 2009; Damsgaard, Christensen, & Rasmussen, 2001; Damsgaard, Rasmussen, Christensen, Surma, & de Zee, 2006; Siemienski, 1992; Vondrak, 2006). These criteria have been extensively discussed (Challis

& Kerwin, 1993; Forster, Simon, Augat, & Claes, 2003; Rasmussen, Damsgaard, & Voigt, 2001). Some muscle recruitment approaches are numerically instable and thus do not display the realistic behaviour (Anybody, 2009b).

Anybody solves the muscle recruitment problem within the inverse dynamics technique by the optimization as described in the following equations:

Equation 2: Optimisation of muscle recruitment.

 $\min_{\mathbf{f} \, G\left(f^{(M)}\right)} \square$

Equation 3: Dynamic equilibrium equation.

Subject to Cf = d

Equation 4: Force generation of muscles.

 $0 \leq f_i^{(M)} \leq N_i \text{ with } I \in \{1, \dots, n^{(M)}\}$

In Equation 2; G is the objective function, i.e. the assumed criterion of the recruitment strategy of the CNS, which is expressed as the muscle forces $f^{(M)}$. G is minimized with respect to all unknown forces such as the muscle forces and joint reactions.

Equation 3 implies the constraints of the optimization and presents the dynamic equilibrium equation. Therefore, C is the coefficient-matrix for the unknown forces while d comprises all known applied loads and inertia forces. Equation 4 expresses that all muscles can only pull while the upper bounds limit their capability since they are unilateral elements and thus generate a force between 0 and N_i as the strength of the muscle (Damsgaard et al., 2006).

It may be considered quite complex to cover physiological processes in formulae but a simplistic view it could be physiologically efficient to minimize the maximum muscle activity so that the maximum relative load of any muscle in the system is as small as possible. This refers to the minimum fatigue criterion and is called the min.-max. muscle recruitment as displayed in Equation 5, i.e. minimization of the maximal muscle activity.

Equation 5: Minimum maximum muscle recruitment.

 $G(f^{(M)}) = \min \max\left(\frac{f_{(i)}}{N_i}\right)$

This form of the objective function has some advantages such as the postponement of muscle fatigue assuming that muscle fatigue and activity are proportional (Rasmussen, 2008). This criterion is deemed to be numerically efficient and robust (Damsgaard & al., 2006). There is no additional need for constraints to avoid muscle overloading since the load and muscle recruitment are proportional. The min.-max. criterion seems to be ideal from a mathematical and physiological perspective, however, it should be implemented with care since some model parts can be independent of each other (Anybody, 2009b).

7.3.4 Twente lower extremity model

The model developed for studies II and III of the current project is based on the Twente Lower Extremity Model (TLEM) (Figure 49). The TLEM is based on a morphological consistent anatomical dataset of lower body musculature and joint parameters from one specimen containing all the required data for the construction of a large scale musculoskeletal model. A total of 55 muscles were included in the model, all of which are divided into different muscle lines of action based on muscle morphology (159 fascicles per leg). Furthermore, it includes seven DOF and 14 ligaments over the hip, knee and ankle (Klein Horsman, Koopman, van der Helm, Prosé, & Veeger, 2007).



Figure 49: Schematic and DoF of the Twente lower extremity model (Anybody, 2009a) The joint degrees of freedom are displayed in Table 7.



| JOINT | DOF | DIRECTION |
|----------------------------|-------------|--|
| Hip | 3 rotations | Flexion/ extension, abduction/ adduction, external/ internal rotation |
| Knee | 1 rotation | Flexion/ extension |
| Ankle | 1 rotation | Plantar/ dorsal flexion |
| Subtalar joint | 1 rotation | Eversion/ inversion |
| Femur / patella segment | 1 rotation | |

 Table 7: Joint degrees of freedom in Twente lower extremity model

The representation of the mechanical effect of the muscles in the model was based on accurate measurement of joint parameters, muscle attachment sites and intervening structures. Parameters that define the muscle moment arm and a sufficient number of muscle elements are included for the precise definition of the muscles so that they are able to curve around geometric shapes or through 'via points' such as bony contours (Van der Helm & Veenbaas, 1991). The TLEM also comprises architectural properties assigned to the muscle elements such as optimal fiber length and tendon length, which are needed for accurate muscle force estimation (Klein Horsman, 2007). Further details about the specifically modified model, called 'Mogul Man' are given within the next sub sections for the implementation of the model.

7.3.5 Implementation of the model

The 'Mogul Man' is the modified full body model including the TLEM and has been developed for the current application. The original full body model was developed for applications such as gait or cycling. In mogul skiing leg flexion and extension angles are similar to cycling and thus compare well with the so-called 'skilled tasks' which are movements with 'normal' ranges of joint movement and angular velocities. Two moving force plates are attached to the feet of the skiers with a differently orientated local coordinate system. The potential resulting difficulties with regard to imprecision or sensitivity of the model were evaluated in a systematic sensitivity analysis as discussed in chapter 7.3.7.

Scaling methods have been implemented which allow the scaling of the segment length masses and fat percentage. This allows the creation of models with specific measures for a certain individuals (Dendorfer & Toerholm, 2008). The model is based on certain model assumptions as listed below:

- Optimal muscle recruitment is given by the muscle model
- hinge joint representation of ankle and subtalar joints
- hinge joint representation of the knee
- model is a collection of rigid segments

Numerous muscles divided in different parts are included in the model. However, a selection of the most relevant muscles for the current analysis have been chosen and are shown in Table 8. The force in the muscle's contractile element, indicated as Fm, is the parameter of interest.

Table 8: Muscle parts included in the model defined as curved muscle elements (CME) and straight muscle elements (SME) with segment of origin and insertion. CL = caputius longus, CB = caputius breve.

| MUSCLE (PART) | CME / SME | ORIGIN | INSERTION |
|--------------------|-----------|--------|-----------|
| Tibialis anterior | SME | Tibia | Foot |
| Soleus medialis | SME | Tibia | Foot |
| Soleus laterali | SME | Tibia | Foot |
| Peroneus longus | SME | Tibia | foot |
| Rectus femoris | SME | Pelvis | Patella |
| Vastus medialis | SME | Femur | patella |
| Vastus intermedius | SME | Femur | patella |
| Vastus lateralis | SME | Femur | patella |
| Biceps femoris CL | SME | Pelvis | Tibia |
| Biceps femoris CB | SME | Femur | Tibia |
| Semitendinosus | SME | Pelvis | tibia |
| Semimembranus | SME | Pelvis | tibia |
| Gluteus maximus | SME | Pelvis | femur |
| Gluteus medius | SME | Pelvis | Femur |
| Gluteus minimus | SME | Pelvis | Femur |
| Iliacus | CME | Pelvis | Femur |
| Adductus longus | SME | Pelvis | Femur |
| Adductus magnus | SME | Pelvis | Tibia |
| Adductus brevis | SME | Pelvis | femur |

The Anybody modelling system contains two different models that are operating consecutively. The first model is for the kinematic analysis and resolves the equations of

motion without muscles and forces. The second model is a progressive continuation that uses the kinematic optimisation data also including muscles and GRF for the calculation of joint loading.

7.3.5.1 Kinematic Analysis

The kinematic analysis in Anybody is called the "Motion and Parameter Optimisation Study". Constraints are associated with the segments. As the segments have a certain number of DoF they also have a certain number of constraints, either given by the connected segments by joints or added to the model by drivers. The number of DoF of the segments and the number of constraints should be balanced. The number of drivers required, needs to be sufficient so to resolve remaining unknowns and of the equation. If this occurs the system is kinematically determinate. The system is deemed to be kinematically over-determinate if there are too many constraints that are incompatible. In turn, if the system has too few constraints or some of them are redundant, the system might become kinematically indeterminate. The last two examples are likely to results in an operation failure. When the AnyBody Modeling System[™] performs the kinematics operation, these drivers are taken through their sequences of values, and the positions of all the segments are resolved for each time step by solving the equations (Anybody, 2009b). The motion of the model, segment scaling and local marker coordinates are calculated from the measured marker trajectories (M.S. Andersen, De Zee, Dendorfer, MacWilliams, & Rasmussen, 2009).

In the kinematic analysis, velocities, accelerations and positions are determined. The latter poses a challenge since the equations are non-linear as opposed to velocities and accelerations which are calculated by linear equations after determination of the positions. In the Motion and Parameter Optimisation study many fine adjustments can be made, e.g. it can be adjusted if a variable or a coordinate of a specific marker should be optimized or left unchanged. The kinematic analysis is the first step of, and the prerequisite to the inverse dynamics operation as described in the following sub section.

7.3.5.2 Inverse Dynamic Analysis

The general principle of inverse dynamics is to process experimental motion data, usually with external forces (e.g. GRF) and to compute the net torques developed at joints by muscles (Zajac & Winters, 1990). It begins with the observed motion or measured forces and moments and calculates the parameters that were leading to the measured values. The

inverse dynamics operation succeeds the kinematic analysis and is similar, however, it is augmented with calculation of forces in the system. The Anybody software can additionally simulate muscle and joint forces in the entire body taking dynamic inertia into account (Figure 50) (Anybody, 2009b).



Figure 50: (adapted from (Rasmussen, Damsgaard, & Christensen, 2001)) Inverse dynamics analysis of one time step.

The difficulty in computing forces in a rigid body mechanical system lies in resolving the equilibrium equations of the forces. If there are not enough equilibrium equations available to resolve the forces, the system may become statically indeterminate. Additionally, the fact that the muscles are only unilaterally pulling constrains the number of possible solutions and thus adds mathematical complexity (Anybody, 2009b). The muscle recruitment problem was solved using the min.-max. criterion with a quadratic penalty (M.S. Andersen et al., 2009). The Newton-Euler equation is employed for the analysis of the movements using inverse dynamics:

Equation 6: Newton Euler equation.

$F = M\bar{r}$

In this equation F is the force, M is the mass and \bar{r} is the second derivative of the position vector. This equation needs to be applied to all segments for a full multi-body analysis. If the Newton Euler equation is for instance applied to a single segment with a hinge joint such as the knee in a simulation (Figure 51) it becomes:

Equation 7: Newton Euler equation applied on hinge joint.

$$F = \begin{bmatrix} F_x \\ Fy - mg \\ -r\sin(\theta)F_y - r\cos(\theta) F_x \end{bmatrix} = \mathbf{M}\bar{r} = \begin{bmatrix} m & \mathbf{0} & \mathbf{0} \\ 0 & m & \mathbf{0} \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$$

In this equation; J is the mass inertia along the rotational axis and F_x and F_y are the reaction forces at the hinge. This is a rather simplified concept, whereas in reality, every segment has an inertia tensor that refers to the centroidal body frame. Every segment, represented by vector F has six DOF, specifically three forces and three moments. This vector F can be subdivided into forces and moments of the muscles, indicated by

Equation 8 (taken from (Damsgaard & al., 2006)): Subdivision of vector F into force and moments.

$$g_i^{(M)} + g_i^{(R)} = g_i^{(app)} - \begin{bmatrix} m_i I & \mathbf{0} \\ \mathbf{0} & J_i' \end{bmatrix} \dot{v}_i - \begin{bmatrix} \mathbf{0} \\ \overline{w}_i' J_i' w_i' \end{bmatrix}$$

In this equation all unknown parameters are on the left side and all known parameters are on the right side. Here \mathbf{v}_i equals \mathbf{r}_i .



Figure 51: Single segment with a hinge joint (example taken from (Koopman, 2008).

The force plates in the current model are attached to the feet including a three degree forward tilt accounting for the elevated heels in the ski boots (Figure 52). The mogul man's neutral stance was determined with a 22 degree plantar flexion angle. This is due to the fact that Anybody defines the natural angle in "normal' movements such as gait between 11 and 13 degrees. The additional forward lean of the mogul man by about 10 percent is due to the slightly flexed neutral position of the ski boot adds up to 22 degrees for all trials. Moreover, the measured ski boot stiffness (chapter 7.2) needed to be incorporated into the model. Hence, the respective boots, as used in study II and II,I were considered to have certain constraints to the ankle joint according to the values gained by

the boot stiffness tests. The appropriately measured stiffness was included in the model as an angle-dependent resistance moment at the ankle joint.

Local forces and moments (x,y,z) applied to each foot served as kinetic input data for the inverse dynamics to calculate knee joint loading. The main focus in the current study was to investigate the knee joint, thus segmental inertial parameters have only been calculated for the lower extremities. However, the upper body was accounted for and reconstructed by a single marker (Table 13), including constraints such as a fixed shoulder, elbow and wrist joints in a typical half flexed skiing position. The orientation of the local coordinate systems of the segments was equally defined throughout as the global reference frame with the x-axis anteroposterior, the y-axis vertical and the z-axis medio-lateral. In contrast, the force plates' local coordinate systems were defined with the x-axis anteroposterior, the y-axis vertical (Figure 52).



Figure 52: Participant during inverse dynamics trial including the GRF reference axis and the segmental local coordinate system for this study.

Further details of the utilized model in Anybody will be discussed within the overall discussion (chapter 10.5). The following sub section will delineate some validation results about the initial model that has been modified for the current project. Additionally, a sensitivity analysis was conducted to verify the reliability of the current data.

7.3.6 Validation of the model

Validations of computer models are a crucial methodological step to evaluate if the model accuracy matches the requirements. However, the available sources with regard to model validation results are limited. Anderson et al. (2009) validated the TLEM by which the 'mogul man' is based using EMG measures. They compared the predicted muscle activities with EMG measurements in gait for an adult and a child sampling motion at 100 Hz and GRF at 1000 Hz using a Vicon Motion Capture System. It was concluded that the model accurately predicted the activity of most muscles during gait. Minor deficiencies were found for the down scaling from the adult to child size and for the prediction of low background EMG.

Other validation studies have been conducted on specific parameters such as muscle moment arms, maximal isometric moments or plantar flexors and knee extensors and showed good reliability of the current model predictions (Dendorfer & Toerholm, 2008; Klein Horsman, 2007).

The mogul man comprises a comprehensive lower body marker set, but only a single upper body marker and upper body constraints as mentioned previously. In two representative trials it was tested if an additional upper body marker set containing manubrium sterni, shoulder, elbow, wrist and upper and lower poles influence the path of the CoM. As expected it was found that the fixed position showed similar values as the upper body marker set condition on the lower body kinetics and kinematics. Hence, for the current application of the 'mogul man' a lower body marker set with only a single upper body marker turned out appropriate for a lower extremity 3D motion reconstruction with realistic dynamical results.

Since the current application of freestyle skiing differs from the motion that the model has been validated for with regard to movement cycle, knee, ankle and hip flexion and extension as well as the GRF values it seemed appropriate to conduct an additional validation in the form of a sensitivity analysis. This will be briefly presented within the following sub section.

7.3.7 Sensitivity analysis

7.3.7.1 Methods

This sensitivity analysis was undertaken to evaluate the model response on selected parameter alterations and to better understand of the consequences of possible imprecisions in the input data.



Figure 53: Left foot with illustration of alteration of force plate position for sensitivity analysis.

In this sensitivity analysis the position of the left force plate was initially altered in three directions to different extends accounting for the effects of possible misalignments. The participants used the same ski boots for testing, however, they had slightly different foot sizes and geometries so that a possible source of error could be a slippage of the foot inside the boot. Thus the extend of the alteration of the force plate's position was chosen 2 cm in anteroposterior, 1 cm in proximal-distal, and 1.5 cm in medio-lateral direction. A total of 15 different alignment variations were tested as presented in Table 9.

The second part of this sensitivity analysis comprised a tilting misalignment of the force plate of 5° around all three axes. The third part included a 2 cm misalignment of the ankle and knee markers of the right side in anteroposterior, proximal-distal and medio-lateral diection (Table 10).

7.3.7.2 Results and Interpretation

Table 9 displays a selection of parameters that were chosen for this analysis as they will be further discussed within the following study chapters (Chapters 9 and 10). The flexion

moment and the lateral moment at the knee show minor errors of 2 % to 4 % for unilateral misalignments of the force plate such as 1.5 cm in medio-lateral direction and 1 cm in proximal-distal direction. The anterior and posterior directions seem to be more sensitive for misalignments and show a 25% error for a 2 cm alteration for the flexion moment and 18% for the lateral moment. The most devastating errors occur if the force plate has an offset in all three directions simultaneously. Errors of up to 31% can be observed for the knee flexion moment for posterior-distal-lateral and anterior-proximal-medial shift of the force plate centre. The greatest error for the knee lateral moment showed the posterior-proximal-medial and the anterior-distal-lateral shift with 32%. The other displayed parameters deviate about 1% to 7% from the neutral position's value (Table 9). Figure 54 illustrates the neutral knee flexion moment plottet against several parameter variations.

Table 9: Alterations of selected parameters in absolute numbers and percentage of change following an intentional force plate misalignment. KNFLEXM=Knee flexion moment, KNLATM=Knee lateral moment, KNANTPOSTF=Knee anterior-posterio force, VASTLAT= Vastus lateralis, HAM=Hamstrings.

| Condition | KnFLex M | % | KnLat M | % | KnAntPostF | % | VastLat | % | Ham | % |
|---------------|-------------|----|------------|----|------------|----|---------|----|---------|---|
| post-prox-lat | 39.69 | 28 | 44.99 | 10 | -9384.84 | 5 | 1689.05 | -2 | 3213.43 | 6 |
| post-prox-med | 43.70 | 20 | 34.13 | 32 | -9503.36 | 4 | 1671.31 | -1 | 3268.73 | 4 |
| post-dist-lat | 37.94 | 31 | 47.42 | 5 | -9334.85 | 6 | 1704.12 | -3 | 3184.11 | 7 |
| post-dist-med | 41.95 | 23 | 36.45 | 27 | -9458.90 | 5 | 1685.43 | -2 | 3230.55 | 5 |
| distal | 53.89 | 2 | 51.14 | -2 | -9888.68 | 0 | 1657.68 | 0 | 3392.46 | 1 |
| proximal | 55.64 | -2 | 48.74 | 2 | -9932.68 | 0 | 1645.98 | 0 | 3429.78 | 1 |
| psterior | 40.82 | 25 | 40.70 | 18 | -9424.53 | 5 | 1687.59 | -2 | 3222.80 | 6 |
| anterior | 68.71 | 25 | 59.10 | 18 | -10394.47 | -5 | 1628.46 | 1 | 3600.11 | 6 |
| lateral | 52.76 | 4 | 55.45 | 11 | -9849.33 | 1 | 1656.86 | 0 | 3384.85 | 1 |
| medial | 56.77 | -4 | 44.50 | 11 | -9965.86 | -1 | 1642.04 | 1 | 3436.35 | 1 |
| neutral | 54.76 | 0 | 49.94 | 0 | -9910.73 | 0 | 1652.08 | 0 | 3410.58 | 0 |
| ant-prox-lat | 67.58 | 23 | 63.38 | 27 | -10360.10 | -5 | 1630.87 | 1 | 3594.37 | 5 |
| ant-prox-med | 71.59 | 31 | 52.51 | -5 | -10475.54 | -6 | 1616.58 | 2 | 3645.95 | 7 |
| ant-dist-lat | 65.83 | 20 | 65.84 | 32 | -10311.46 | -4 | 1636.30 | 1 | 3559.44 | 4 |
| ant-dist-med | 69.84 | 28 | 54.90 | 10 | -10427.05 | -5 | 1626.00 | 2 | 3607.06 | 6 |



Figure 54: Left knee flexion moment neutral plottet against variations in posterior, anterior, lateral, medial, proximal and distal directions.

Results for a greater selection of parameters are attached as appendices 6-8. The analysis of the error values suggest that an unintentional offset of the force plate's position is critical with regards to altered measurements compared to the neutral position. However, if both conditions are equally defined the only possible source of error for each participant may be the marker positions on the reference ski boots that differ slightly in geometry. Due to different marker placements the optimization of the model may change the definition of the foot. However, the investigators endeavoured to place the markers identically on the boots for both conditions.

According to Challis & Kerwin (1996), the main sources of error in estimating joint moments are the kinematic parameters, i.e. the deratives of the position data. An alteration of the knee joint centre position of 0.01 m in anteroposterior direction in gait resulted in 30% variation of the flexor peak force (Holden & Stanhope, 1998). Ramakrishnan et al. (1991) varied joint centersat the ankle, knee and hip by 0.01 m about all anatomical axes and found the smallest variations in the flexion extension moment of the ankle was 7%. The abduction-adduction moment of the ankle revealed maximum errors of 33%. Maximum errors of joint centre location in the current study were assumed to be greater than in the previously described studies. However, these authors described maximum errors in peak values, whereas the average errors in lower extremity joint moments elicited by alterations of the joint centre position remain unknown.

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Table 10 demonstrates the extent to which a marker misalignment of 2 cm and a force plate tilt of 5° can distort the kinetic output as tested in the current project. The knee moments turned out to be most sensitive to marker displacements if both the ankle and the knee marker were displaced with alterations of approximately 35%. Also posterior ankle marker displacement and lateral knee marker displacements exhibited a large error with 35% and 27% change. The anteroposterior knee force only altered between 1% and 10% and was most sensitive to lateral knee marker displacement. The vastus lateralis and hamstring muscles showed only minor changes of 0% to 6%. A 5° forward tilt of the force plate had the most devastating effect on the knee moments with up to 84% distortion (Table 10).

This sensitivity analysis was conducted to be able to estimate the possible effects of imprecisions in the placement of the force plate and markers. The predictions of the current model, however, are assumed to be more precise than the changes in this analysis.

| condition_marker | LKnFlexmax [%] | LknLatM_max [%] | LKnAPNNeF [%] | LVastLat [%] | LHam [%] |
|------------------------|-------------------|--------------------|------------------|-----------------|-------------|
| Reference | 0 | 0 | 0 | 0 | 0 |
| AnkleXplus2 | 13 | -12 | 8 | -3 | 6 |
| AnkleXminus2 | -35 | -34 | 1 | -1 | -5 |
| KneeXplus2 | -11 | -22 | 4 | -1 | 0 |
| KneeXminus2 | -12 | -22 | 4 | -1 | 0 |
| Knee&ankleXplus2 | 13 | -12 | 8 | -3 | 6 |
| Knee&ankleXminus2 | -35 | -34 | 1 | -1 | -5 |
| KneeXplus2ankleXminus2 | -34 | -34 | 1 | -1 | -5 |
| KneeXminus2ankleXplus2 | -35 | -34 | 1 | -1 | -5 |
| KneeZplus2 | -27 | -19 | 10 | -2 | 2 |
| KneeZminus2 | 0 | 0 | 0 | 0 | 0 |
| RightKneeXplus2 | -11 | -22 | 4 | -1 | 0 |
| RightKneeXminus2 | -11 | -22 | 4 | -1 | 0 |
| condition_force plate | | | | | |
| Xplus5degree | -35 | 24 | 2 | -1 | -6 |
| Xminus5degree | 1 | -56 | 1 | -3 | 2 |
| Yplus5degree | -84 | -52 | -3 | 1 | -17 |
| Yminus5degree | 45 | 6 | 4 | -5 | 13 |
| Zplus5degree | -10 | -20 | 4 | -3 | 0 |
| Zminus5degree | -10 | -20 | 4 | -3 | 0 |

Table 10: Alteration of selected parameters in percentage of change following an intentional misalignment of selected markers and the force plate.

Chapter 8: Study Two: On mountain data collection – verification of a testing approach including an assessment of a ski boot modification on biomechanical parameters in freestyle skiing

8.1 Introduction and purpose

The previous chapters provided a description of the process of verification of the methodological approach towards a field experiment on the effect of boot modifications on joint loading in mogul skiing. In particular the motion capture system was evaluated with regard to the expected requirements in the field. The feasibility of the calibration method was confirmed and kinematic data on a skiing movement was collected in an artificial on-snow environment (study I). Second, the effect of the measurement device on skiing performance as well as skiers' perception was tested. Third, a modelling environment was explored with regard to its applicability to the problem.

The missing components are the selection or development of a suitable force measurement device and the verification of the whole testing and data analysis pipeline under outdoor, on-snow conditions. With these steps accomplished it was consequently aimed at conducting a pilot study to implement the approach. Therefore, in this chapter a pilot study is described which aimed at investigating a mogul skiing resembling movement as well as including a boot modification. As the modification of the boots was still under development an approach previously used for training in alpine race skiing was selected that implied the removal of the shaft (Hild, 2009). The boot intervention needs to be conceived as a coordination training tool rather than an applicable modification for competition or regular use. This investigation was conducted in a wave course as described previously (Machens, 2006). Additionally, the suitability of a force measurement device developed by Kiefmann (2006) was implemented and compared to pressure insole measurements which were described in the literature (Raschner, Schiefermueller, Zallinger, Hofer et al., 2001; Schaff & Hauser, 1989). All data were used as input for the previously introduced 'Mogul Man' referred to as the utilised computer model specified for mogul skiing.

A systematic analysis of freestyle-specific movements with specifically verified measurement equipment enables the creation of a database on mechanical demands and

loading experienced by athletes. The results of study II and study III will be merged in an overall discussion later on (chapter 10).

8.2 Hypotheses

As this is a feasibility study the main goal was to verify the process as such. To do this an intervention known from coaching was taken. With regard to the effects of this intervention the following hypotheses were formulated:

- **Hypothesis II.a):** Ankle flexion range of movement will be increased with the modified ski boot.
- **Hypothesis II.b):** Participants will be able to ski with a greater forward lean with the modified boot.
- **Hypothesis II.c):** Range of movement and in particular the maximum flexion angle at the knee will be greater with the modified ski boot.
- Hypothesis II.d): Normal GRF will be reduced using the modified boot.
- **Hypothesis II.e):** Net joint forces on the ankle and knee joint will be reduced with the modified boot.
- **Hypothesis II.f**): The constraint moments will not change between conditions.
- **Hypothesis II.g):** Calculated muscle activation in the vasti muscles, hamstrings and gastrocnemius will be lower when wearing the modified ski boot.

8.3 Methods

8.3.1 Subjects

A total of five male skiers (27.8 y. \pm 11.9 y.) participated in this study (Table 11). Prior to testing, all participants signed a consent form and were then asked to complete a questionnaire which screened for potential contraindications to the assessment protocol. This questionnaire also addressed skiing and general sporting experience, and the individual's preferences with regard to equipment and environmental challenges (appendix 3). For the current study participants ranged from recreational to expert as the aim of this intervention was to find out about the applicability of this training tool for the broad freestyle skiing community. Only male participants volunteered for the current

study.

| Participant [n=5] | Age [years] | Gender [m/f] | Body height [cm] | Body weight [kg] | Experience [years] |
|----------------------|----------------|-----------------|------------------------|------------------------|-----------------------|
| P1 | 16 | Μ | 187 | 81 | 10 |
| P2 | 16 | Μ | 174 | 73 | 11 |
| P3 | 32 | Μ | 189 | 89 | 20 |
| P4 | 31 | Μ | 179 | 80 | 27 |
| P5 | 44 | М | 179 | 95 | 20 |
| Mean | 27.8 | M=5 | 181.6 | 83.6 | 17.6 |
| SD | 11.9 | | 6.2 | 8.5 | 7.1 |

Table 11: Anthropometric data study II.

8.3.2 Testing procedures

All testing took place on the Zermatt ski field, Switzerland and the experimental procedures were given ethical approval by the University of Auckland Human Participants Ethics Committee (Ref 2007/106).

All participants initially trained for at least four hours with the new boots on the normal slope as well as on the testing course. They were instructed to exercise bending and straightening movements in order to get accustomed to the altered flexibility of the boots. The familiarisation phase was conducted progressively, first with just the modified ski boot and after 2 hours with both the new boot and a mock-up of the force plate in order to get used to the real testing condition. Subsequently three runs with these modified boots were tested before another three runs with their ordinary equipment (Figure 55).



Figure 55: Testing process of study 2.

All participants were filmed during three runs wearing the modified exercise ski boot with no shaft (NS condition) performing bending and straightening movements in the wave slope whilst GRF and associated moments were collected simultaneously (Figure 56).



Figure 56: Participant during trial.

Afterwards they swapped and completed another three runs wearing their conventional ski boots with shaft (WS condition).

Additionally, three runs on the slope performing short turns were investigated in order to compare values measured by the applied force measurement device with values measured by pressure sensitive insoles.

Hopping movements were executed before each run to facilitate subsequent synchronisation of the footage with the force data. All field testing took two weeks for two investigators including the set up of the test slope and all measuring equipment. Figure 57,a) shows one investigator operating the stationary computer and thus the cameras and Figure 57,b) shows the other investigator preparing a participant for testing.



Figure 57: a) Investigator operating the computer for kinematic data collection, b) Investigator preparing participant for test run.

8.3.3 Measurement equipment

For acquisition of kinetic data the ski force plate as described in the previous chapter was utilised (Figure 58). It was clicked into the binding of the same testing ski as used in study I (chapter 5.3.2). Amplifiers were strapped on the legs close to the device and both batteries and the data logger were housed in a small backpack worn by the participants during the trials. Data was sampled at 500 Hz.

Additionally, a Pedar insole measurement system was employed to compare the force measurement output with plantar pressure data. One plantar sole was utilized under the right foot and a 'dorsal pad' that had a similar shape as an insole, but shorter, was placed at the shin (Novel GmbH, 120 Hz). A Biovision data collection system and a digital video camera (Sony, 25/50 Hz) were used.



Figure 58: Ski force plate attached between ski boot and binding.

For modification of the boot, the ski boot's shaft was removed and the residual material at the back of the boot was made more bendable by milling an 80 mm cut down the rear spoiler in order to gain a noticeable greater flexibility in both anterior and posterior direction (Figure 59). Three pairs in different sizes were made available from the Head ski boot company for this study (sizes 28.0, 28.5, 29.0).



Figure 59: First ski boot modification (Head Raptor Super Shape): a) greater flexibility in anterior direction; b) 80mm cut in rear spoiler to withrdraw resistance in posterior direction.

The testing procedures required the components as shown in Table 12.

| ITEM | AMOUNT | BRAND |
|--|--------|-------------------------------------|
| High speed cameras | 4 | Basler A602f |
| Digital video camera | | Sony |
| Camera tripods | 4 | |
| Stationary computer including monitor, keyboard, mouse, Simi Motion software | 1 | Custom-made Software version 266 |
| Camera cable and genlock connection cable | 100 m | |
| Hubs (to connect camera cables) | 8 | |
| Genlock adapters | 4 | National Instruments PCI – 6024E |
| Calibration rod with 3 reflective markers attached (2 m) | 1 | Custom made |
| Ice buckets for tight camera tripod positioning | 16 | |
| Theodolite for kinematic calibration | 1 | Geodimeter [®] System 600 |
| Big tripod for theodolite | 1 | |
| Racing suit attached with markers | 1 | |
| Skis and poles | 1 pair | Head Super Shape, Leki |

Table 12: Testing equipment used in study II.

| ITEM | AMOUNT | BRAND |
|--|---------|----------------------------|
| Modified ski boots in size 28.0, 28.5, 29.0) | 3 pairs | Head Raptor Super Shape |
| Ski force plates | 2 | Custom made |
| Batteries (7.2V at 2500 mAh, stabilised on 5V input voltage) | 2 | |
| Mini PC as data logger | 1 | Sony Vaio Micro PC UX 380N |
| Amplifiers (250 fold for Z, 500 fold for X and Y) | 2 | custom made |
| Diesel-generator for power supply | 1 | Honda EX 100 |
| Data collection system | 1 | Biovision |
| Pedar plantar sole + doral pad | 1 / 1 | Novel GmbH |

8.3.4 Kinematic setup



Figure 60: Testing slope, downhill view.

This investigation was carried out in a wave slope of 19° inclination with six bumps of 0.5 m height situated at a distance of 4 m to each other (Figure 60). Bumps number three and four framed the recorded area in order to collect the data within a fluent motion cycle. The temperature varied slightly throughout the testing days between -5°C and -10°C. The testing area was snow-covered twice within the testing days so that reconstruction of the test slope was necessary. The visibility also varied within each testing day from foggy to sunny and the wind intensity changed as well. Hence even though the test slope was arranged in a fenced area, it was difficult to keep the conditions constant at all times.



Figure 61: Participant with black markers attached on race suit, a) front view; b) back view.

Four high speed cameras were collecting videos of the performance in a 10m by 3m area at a frequency of 50 Hz. The upper cameras and the lower cameras were situated beside the test slope on tripods, which stood in ice buckets to prevent any disruptive movements. The angle of any two optical axes was about 60 degrees and the cameras had a distance of seven to ten metres to the recording volume (Figure 32). The camera cables and connection cables of the genlock adapters were run beneath the snow in cable channels through the testing slope.

The marker set of study I was slightly modified for this study. A set of 27 black markers (19 dynamic plus 8 static) were fixed to the skier bilaterally on bony landmarks to define the bodyparts as listed in Table 13. These were affixed with adhesive tape on a red racing suit worn by the participants (Figure 61).

| BODY SEGMENT | MARKER NAME | LOCATION |
|--------------|-------------------------|--------------------------------------|
| Trunk | CLAV | Cranial end of the sternum |
| Hip | RASI | Right anterior superior iliac spine |
| | LASI | Left anterior superior iliac spine |
| | RPSI | Right posterior superior iliac spine |
| | LPSI | Left posterior superior iliac spine |
| Right thigh | RTHIPROX | Right quadriceps proximal |
| | RTHIDIST | Right quadriceps distal |
| Left thigh | LTHIPROX | Left quadriceps proximal |
| | LTHIDIST | Left quadriceps distal |
| Right knee | RKNELAT | Lateral epicondyle of femur |
| | RKNEMED (static) | Medial epicondyle of femur (static) |

Table 13: Marker placements.

| BODY SEGMENT | MARKER NAME | LOCATION |
|-------------------|--------------------|-------------------------------------|
| Left knee | LKNELAT | Lateral epicondyle of femur |
| | LKNEMED (static) | Medial epicondyle of femur (static) |
| Right shank | RTIB | Medial to tibia |
| Left shank | LTIB | Medial to tibia |
| Right foot | RTOE | 2 nd phalanges distales |
| | RHEE | Posterior to calcaneus |
| | RANKLAT | Lateral malleolus |
| | RANKMED (static) | Medial malleolus (static) |
| Left foot | LTOE | 2 nd phalanges distales |
| | LHEE | Posterior to calcaneus |
| | LANKLAT | Lateral malleolus |
| | LANKMED (static) | Medial malleolus (static) |
| Equipment markers | RFRONTBIN (static) | Right front binding |
| | RREARBIN (static) | Right rear binding |
| | LFRONTBIN (static) | Left front binding |
| | LREARBIN (static) | Left rear binding |

8.3.5 Kinematic calibration

The kinematic calibration procedure for this study was the same as in study I (chapter 5.3.5, Figure 62).



Figure 62: Pole with three markers attached on testing bump for kinematic calibration.

8.3.6 Ski boot flexibility tests

For all relevant conditions, specifically using a normal ski boot with shaft (WS), a ski boot with no shaft (NS) plus a barefoot trial (BF) as reference, the ankle angle and the range of List of research project topics and materials

motion of the ankle joint and the ski boot have been measured for comparison in a laboratory environment (Figure 63).



Figure 63: Laboratory based tests of ankle range of motion and ski boot range of motion under a) barefoot (BF), b) ski boot with no shaft (NS), c) normal ski boot with shaft (WS) condition.

A ski binding was mounted tight on the floor so that a ski boot could be clicked in. Five (six for NS and WS) retro-reflective markers with a diameter of 25 mm were affixed to the toe, the heel, the pivot point at the ankle joint and at the shaft of the boot as well as laterally to the shank and to the knee. The anteroposterior range of movement and the maximum dorsal flexion of the ankle joint were measured in the sagittal plane using a single camera of a Simi Motion System. The participant was instructed to move the tibia from the neutral position as far forward as possible and back to the neutral position. The range of movement of the ankle joint was calculated and compared by the angle evolved from the lines of the knee, shank and the ankle joint markers representing the shank, and the toe and the heel markers representing the foot. For the ski boot range of movement the markers on the upper shaft and the pivot point of the ankle and the two foot markers were used. Table 14 presents the numbers for the neutral, the minimum and the maximum angle for all three conditions for the remainder of this chapter.

Table 14: Ankle angle and range of motion ankle joint and ski boot (WS = with shaft, NS = no shaft, BF = barefoot).

ankle joint

| | neutral | min | max | range of motion front flex |
|----------|-----------------------|-------------------|------------|---|
| WS | 67° | 42° | 87° | 25° |
| NS | 72° | 37° | 96° | 35° |
| BF | 84° | 46° | 121° | 38° |
| | | | | |
| | | | als: haa | 4 |
| | | | SKI DOO | n an |
| | neutral | min | max | range of motion front |
| | neutral | min | max | range of motion front flex |
| WS | neutral 74° | min 65° | max 78° | range of motion front flex 9° |
| WS NS | neutral 74° 72° | min 65° 69° | 78° 81° | range of motion front flex 9° 3° |

The ankle joint range of motion from the neutral position to the maximum forward lean position NS was 10° greater compared to WS. Whereas the ski boot flexibility in anterior direction with NS was only 6° greater than WS. One has to keep in mind, however, that even while wearing a ski boot the ankle flexibility is always greater than the ski boot flexibility due to the expandable shoe tongue (Table 14). This effect is even greater without a shaft, because the foot is moving relatively free without bending the boot noticeably. The maximum forward range of motion in the BF condition is with 38° only slightly greater than in the NS condition (35°).

8.3.7 Data analysis

Data of two participants were processed for this study for both kinetic and kinematic parameters. Another three participants were analysed with regard to the kinematic parameters. Three runs per condition were digitised for all participants, specifically three runs with the modified exercise ski boots (NS) followed by another three runs with normal ski boots (WS). Kinematic data were processed off-line initially using Simi Motion Software. The consecutive work steps in Simi Motion comprised the camera calibration, specification of the markers for digitisation, the digitisation itself and the calculation of the 3D marker coordinates using the Direct Linear Transformation (DLT) technique (Chen, Armstrong, & Raftopoulos, 1994).

Force data were converted in an ASCII format by the Dasylab software (National Instruments Ireland Resources Limited). A custom-made MATLAB script (Mathworks, USA) converted these files subsequently into txt files as required for synchronisation in Simi Motion. Since kinematic and kinetic data were collected at different sampling frequencies they were re-sampled for further processing. For synchronisation in Simi Motion reference movements such as stepping and hopping visible in one of the genlocked cameras were performed. The files with all tracked three dimensional trajectories were

exported from Simi Motion including both kinematic and kinetic data. A low-pass filter and a cut off frequency of 10 has been used as recommended by Corazza & Cobelli (2005) for proper ski boot design and simulation.

Another custom-made MATLAB script separated the exported files into as many files as markers, forces and moments were given including a timeline and the coordinates. These files were subsequently imported into the Anybody modelling softwareTM for further processing along with participant specific adjustments such as trial length and segment length. The CSV-Anybody output file were read into Excel for final calculations of means and standard deviations as well as the direct comparison of the two conditions on various parameters (chapter 7.3.5.1, 7.3.5.2). The volume of interest included two moguls with the starting point just before the first peak and the end point just behind the second peak to ensure two complete movement cycles. This has been defined using a pre-arranged excel sheet.

For kinematic analysis the specifically modified model has been implemented as decribed in chapter 7.3.5. The relevant outcome measures for the current study were:

- Ankle flexion and extension angles
- Knee flexion and extension angles
- Hip flexion and extension angles
- Anteroposterior position of the CoM in relation to a point halfway between both ankle joint centres indicating the relative forward lean
- Medio-lateral position of the CoM in relation to a point halfway between both ankle joint centres indicating the relative side lean

Data were originally collected at two different sampling frequencies (500 Hz for kinetics, 50 Hz for kinematics), thus after synchronization they were time normalized and interpolated using a spline algorithm when required. For the kinetic analysis the following parameters were calculated:

- GRF and associated moments
- Ankle joint force and moments
- Knee joint force and moments
- Hip joint compression force
- muscle activity (see muscles in Table 8)

For comparison of joint forces and moments with other studies, the local coordinate systems must be the same to avoid measurement differences. For the current study forces and moments at the knee joint were calculated using the local coordinate system of the tibia as it was common in other studies (Figure 64) (Herzog et al., 1993; Nachbauer & Kaps, 1996; Read & Herzog, 1992).



Figure 64: Definition of the local coordinate system of the tibia.

The modified boot in this study was considered having no additional constraints to the ankle joint, whereas the normal boot did restrict the movement. This movement restriction was implemented in the model according to the measured stiffness values (chapter 7.2) as explained in the previous chapter.

For comparison of the force data with the plantar pressure data the distance of the CoP to the centre of the force plate (Figure 65, black cross) was used to calculate the moment on the force plate about the medial lateral axis. Figure 65 displays the split of the pad resulting force of the shaft into anterior and normal direction whereby the grey arrows indicate the CoP coordinate.



Figure 65: Ski boot with indication of force application at front shaft and boot sole.

The coordinates of the COP were exported. All data were synchronized and merged using a custom-made MATLAB script. Calculations resulted in the total vertical force and total moment as calculated from the pressure measurements.

Only descriptive statistics were used since only two skiers were tested using the full data set. Five participants were tested kinematically and additionally under just one boot condition (WS) for turns on the normal slope and absorbing movements in the wave slope comparing the pressure system to the forceplate.

8.4 Results

In the results section, two movement cycles in the wave slope are presented per trial. Two participants are presented by forces, moments, joint angles and muscle activation of both legs. Results from another three participants are only displayed for kinematic parameters. Selected runs will be displayed for the comparison of pressure measurements to the force plates' output data. The z component of the GRF is the normal direction with respect to the snow surface as long as the ski stays in contact with the ground. Thus this component is named 'normal GRF' for the remainder of the thesis.

8.4.1 Kinematics

The results show changes in kinematic parameters mainly for the ankle joint. A greater maximum ankle joint flexion angle as well as a greater ankle joint range of movement was
found when wearing the modified ski boot in the NS condition. The maximum ankle flexion increased from 12° and 7° to 20° and 18° from the WS to the NS condition (right / left). The range of movement was approximately 65% larger for the left side with 22° in the NS condition compared to 13° in the WS condition. The range of movement on the right side remained the same at 19° (Figure 66). The greatest ankle flexion angles reached 40° for a single participant (no.4). Ankle angle at peak force is smaller with 11.2° on the left foot in the NS condition compared to 2.3° in the WS condition



Figure 66: Ankle joint flexion range of movement.

The horizontal distance of the CoM in relation to a point halfway between both ankle joint centres indicating the relative forward lean showed minor differences at force maximum with 4 cm in the NS and 6 cm in the WS condition. Positive values indicate a position in front of the reference point, i.e. a forward lean, negative values indicate a position behind the reference point, i.e. backward lean. However, the average forward lean over the runs is greater in the WS condition with 2 cm as compared to -5 cm in the NS condition (Table 15, Figure 67). The range of motion is with 41 cm in the WS condition also larger than 36 cm in the NS condition.



Figure 67: Position of the body's CoM with respect to a point halfway between both ankle joint centers indicating the average forward lean for both conditions.

The knee joint angles remained for both legs for the minimum and maximum values constant in both conditions (Figure 68). The same holds true for the hip joint flexion angle with a minor alteration towards a greater angle in the WS condition.





All kinematic values for the individual participants including the average minimum and maximum joint angles and ranges of movement are displayed for both conditions in Table 15.

| | Part | . 1 | Part | . 2 | Part. | . 3 | Part | . 4 | Part | . 5 |
|---------------------|----------|-----|------|-----|-------|----------|----------|-----|------|-----|
| Parameters | NS | WS | NS | WS | NS | WS | NS | WS | NS | WS |
| RKneeFlexMax [deg] | 77 | 59 | 90 | 98 | 78 | 88 | 103 | 103 | 79 | 70 |
| RKneeExtMax [deg] | 29 | 27 | 32 | 41 | 40 | 25 | 43 | 46 | 41 | 46 |
| RKneeRange [deg] | 49 | 33 | 58 | 57 | 38 | -c 63 | 60 | 57 | 38 | 24 |
| LKneeFlexMax [deg] | 72 | 60 | 87 | 97 | 59 | 90 | 105 | 94 | 69 | 52 |
| LKneeExtMax [deg] | 25 | 23 | 32 | 45 | 32 | 35 | 35 | 35 | 34 | 22 |
| LKneeRange [deg] | 48 | 37 | 55 | 52 | 28 | 55 | 70 | 59 | 35 | 30 |
| RAnkleFlexMax [deg] | 7 | -3 | 10 | 6 | 19 | 22 | 40 | 17 | 23 | 17 |
| RAnkleExtMax [deg] | -9 | -17 | -2 | -16 | 3 | 0 | 9 | -2 | 1 | -3 |
| RAnkleRange [deg] | 17 | 14 | 12 | 21 | 16 | 23 | 31 | 20 | 23 | 19 |
| LAnkleFlexMax [deg] | 7 | -4 | 15 | 8 | 13 | 11 | 40 | 8 | 13 | 9 |
| LAnkleExtMax [deg] | -18 | -20 | -2 | -2 | -10 | -4 | 3 | -2 | 3 | -7 |
| LAnkleRange [deg] | 25 | 15 | 17 | 11 | 23 | 15 | 37 | 10 | 10 | 17 |
| RHipFlexMax [deg] | 23 84 | 84 | 111 | 123 | 100 | 105 | 114 | 124 | 93 | 98 |
| RHipExtMax [deg] | 20 | 22 | 13 | 53 | 53 | 38 | 38 | 50 | 12 | 38 |
| RHipRange [deg] | 20 64 | 63 | 68 | 70 | 18 | 67 | 50 77 | 73 | 50 | 61 |
| LHipFlexMax [deg] | 04 84 | 82 | 115 | 127 | 100 | 108 | 114 | 110 | 00 | 100 |
| LHipExtMax [deg] | 21 | 21 | 113 | 52 | 100 | 100 | 30 | 119 | 38 | 35 |
| LHipRange [deg] | 63 | 62 | 73 | 75 | 51 | 61 | 75 | 73 | 61 | 65 |

Table 15: Mean values of kinematic parameters for three runs per condition per participant (FlexMax=maximum flexion, ExtMax=maximum extension, NS=no shaft, WS=with shaft, Part.=participant).

8.4.2 Kinetics

GRF were calculated using the local coordinate system of the ski force plate (Figure 52). Mean GRF and moments acting at the boot soles of both legs for two participants are displayed in Figure 69 for both the NS condition and the WS condition.



Figure 69: Mean of maximum and minimum normal GRF.

The normal force F_z is the main components of the resultant GRF as the performance only comprised vertical movements of the legs. The GRF is approximately 16% and 7% larger in the WS condition with 12 N/kg and 11.5 N/kg compared to 10.13 N/kg and 10.71 N/kg in the NS condition. The anteroposterior as well as the medio-lateral forces are negligible as shown in an exemplary illustration for one participant (Figure 70).



Figure 70: GRF of participant no.2 in a single NS run (ap=anteroposterior, md=mediallateral, n=normal.

The net compression forces on the knee joint decreased for the right side approximately 37% from 95 N/kg to 60 N/kg from the WS to the NS condition. However, the left side remained at the same values of approximately 74 N/kg. The minimum values decreased

between 70% and 80% on both sides, so that the range was also larger for the left side (Figure 71,a). The anterior knee forces were between 14% and 22% greater in the NS condition with -36.92 N/kg and -42.53 N/kg compared to -32.21 N/kg and -34.63 N/kg in the WS condition (Figure 71,b). Femoro-patellar compression forces decreased from -24 N/kg and -41.53 N/kg to -17.82/kg and -22.98 N/kg from the WS to the NS condition (Figure 71,c).









Figure 71: a) Net compression forces, b) net anterior forces, c) net femoro-patellar forces on the knee joint.

The knee flexion moments indicated by the positive values show an ambiguous trend with a 40% decrease on the right side from 1.79 Nm/kg/m to 1.06 Nm/kg/m. On the left side the moment increase from 0.83 Nm/kg/m to 1.51 Nm/kg/m. The extension moments indicated by the negative values were negligible on the right side in both conditions and increased on the left side from 0 to -0.86 Nm/kg/m (Figure 72,a). The knee internal-external rotation moment was reduced in the NS condition from -0.6 Nm/kg/m and 0.43 Nm/kg/m to -0.29 Nm/kg/m and 0.29 Nm/kg/m (Figure 72,b). The lateral moments are greater for values on the right side in the WS condition with 0.55 Nm/kg/m. The right side does not show a varus moment on the WS condition. The left side shows a valgus moment of 0.41 Nm/kg/m and a varus moment of -0.22 Nm/kg/m the in the NS condition whereas the WS condition does not show a valgus moment, but a more than three times larger varus moment with -0.73 Nm/kg/m (Figure 72,c).



Figure 72: Net moments for the knee, a) flexion-extension, b) internal-external rotation (axial), c) varus-valgus (lateral).

8.4.3 Muscle activation

The muscles show almost exclusively higher activation values for the WS condition than for the NS condition. These values are noticeably different for some muscles between the left and the right leg. The vasti muscle group exhibits the greatest values for the vastus lateralis as displayed in Figure 73. The vastus lateralis activation decreased between 50% and 70% from the WS to the NS condition from 9.98 N/kg and 13.60 N/kg to 4.47 N/kg and 4.41 N/kg. Vastus medialis and vastus intermedius activation also showed a reduction of the same percentage at lower values for both legs (Figure 73).



Figure 73: Average muscle activation of the vasti muscle group in both conditions.

The muscle activation of the hamstrings was similar in both conditions for the right leg at approximately 25 N/kg. The activation on the left leg was approximately 50% higher in the NS conditions with 25.80 N/kg compared to 16.68 N/kg in the WS condition (Figure 74).



Figure 74: Average muscle activation of the hamstrings in both conditions.

The gastrocnemius muscles were approximately three to seven times more activated in the WS condition than in the NS condition. The gastrocnemius medialis reached the highest values of 15.96 N/kg on the right and 9.88 N/kg on the left compared to 2.21 N/kg and 3.34 N/kg in the NS condition (Figure 75).





8.4.4 Pressure insole measurements

All results for comparison between pressure data and force data are for the WS condition in the wave slope and additionally on the normal slope for short turns (displayed as 'turns'). Although correlations were observed the peak values showed large differences between the two measurements (Table 16). The highest similarities for the forward moment were found in turns. Forces transmitted to the frontal shaft reached up to 1.5 BW.

| F _{normal} | Correlation | bias | | | |
|--|--|---------------------------|----------------------------|--|--|
| | | Sole | Sole & Pad | | |
| Reference | 0.4 - 0.91 | -40% | -30% | | |
| Turns | 0.9 - 0.93 | -24% | -21% | | |
| Wave | 0.6 - 0.89 | -34% | -24% | | |
| м | Convolution | bias | | | |
| М | Convolution | bias | | | |
| $\mathbf{M}_{\mathbf{forward}}$ | Correlation | bias Sole | Sole & Pad | | |
| M _{forward} Reference | Correlation 0.3 – 0.71 | bias Sole -71% | Sole & Pad -25% | | |
| M _{forward} Reference Turns | Correlation 0.3 - 0.71 0.8 - 0.83 | bias Sole -71% -85% | Sole & Pad -25% -17% | | |

Table 16: Correlations and bias for comparison of pressure and force measurements.

8.5 Discussion

The current study was a feasibility study verifying a testing and analysis pipeline. Therefore a mogul skiing resembling movement was investigated using a comprehensive setup of measurement devices and a computer model for comparison of two different ski boot conditions. Five participants were tested but due to technical problems with the force plate design only kinetic data of sufficient quality were accessible for two participants. Thus results of five kinematic and two full data sets showed minor kinematic and kinetic changes whereas larger changes regarding the muscle activation were found comparing the two conditions. No statistical analysis has been conducted. The underlying idea of this boot alteration as a training tool was to allow for a natural squatting movement when flexing the legs to absorb a mogul and reduce the joint loading on the knee (chapter 4). This principle has been used for other disciplines previously.

For most participants the training period turned out to be insufficient to make use of the greater forward flexibility of the boot and thus a different technique. These participants rather remained in their conventional movement patterns. However, the training period with the modified equipment turned out to be vital for representative results because the greater dorsiflexion and less stability required adaptation to a different technical execution. Short training periods can be problematic in that common and automatised movement patterns are usually blocking the acquirement of new but similar movement

patterns. In neurophysiology this is called 'priming', i.e. a stimulus or sensation that a person has been exposed to before is recognized even though this stimulus or sensation is only similar or incomplete (Kassat, 1998). Hence, the process of relearning or unlearning such kind of movement is often exacerbated by the already automatised movement patterns and thus requires time for familiarisation. In mogul skiing related movements as relevant for the current study a period of three days for familiarization has been shown to be useful to get accustomed to a different stance on the ski. This extended training period was given for a single participant who showed a better adaptation with an increased maximum ankle angle of 30° and 37° in the NS condition compared to 19° and 10° in the WS condition. Further he exhibited a two times greater range of movement in the ankle joint, an up to 10° greater knee joint range of movement as well as maximum angle and a more distinct forward lean of 13 cm (Figure 76).



Figure 76: Test runs of participant 4 after three full days of familiarisation with leg flexion on the bump and leg extension in the valley between bumps; a) modified ski boot with no shaft (NS), b) normal ski boot with shaft (WS) (AA: ankle angle; KA: knee angle).

Figure 77 displays the knee angles over time for participant 4 for both conditions and shows a greater range of motion in the NS condition.



Figure 77: Knee angles in a run of a single participant a) right knee NS and WS, b) left knee NS and WS. RKnFLex=right knee flexion, LKnFlex=Left knee flexion.

A strict standardization for the training period was not considered crucial as the major goal of this study was the verification of the process. However, this aspect was considered vital for the implementation of study III. Participant 4 (Figure 76) was the only participant who trained for a full period of three days with the modified exercise boot. This is presumably reflected in the results that differ discernibly in an intra-subject as well as in an intersubject comparison. A change in maximum knee extension angle for participant 4, specifically straightening the legs in the dips between the moguls, suggests a more active vertical absorbing movement with the modified boot which is crucial for mogul skiing technique. A greater anteriorly directed ankle range of movement may have caused the forward shifted CoM during the test runs in the NS condition. This may have caused a

reduction of the load on the passive structures of the knee. However, no inverse dynamics could be applied to this participant. These distinct changes were not found in other participants. Hence, hypothesis II,a) is only supported by the right leg in average showing a greater ankle range of movement, but not by the left leg. Hypotheses II,b) and II,c) can only be confirmed for participant 4, but not for the average of participants which is presumably attributed to the lack of training time. Additionally, it is assumed that a lack of forward lean resistance led to a tendency to lean back at instant of impact absorption to maintain balance and avoid falling over. Thus the boot modification may have been too drastic to gain a natural squatting movement above the base of support.

Despite no clear kinematic alterations were found for most participants and most parameters all participants showed a decrease of GRF, which confirms hypothesis II,d). Lower averages of GRF imply a less accelerated CoM. However, changes for joint forces and moments were analysed without a consistent trend and with inconsistencies between legs (see figures 72 and 73). Besides the lack of training time a possible explanation for the asymmetric leg loading is that the lower body kinematic strategy was adjusted by some participants in the way that an additional impact buffer was shared between the ankle, knee and hip joint almost evenly. Therefore only slight changes to each joint in conjunction with a more active absorption by quickly pulling up the legs could theoretically have that effect. These changes are not reflected by the anteroposterior forces on the tibia, however, the femoro-patellar compression forces support this explanation. Thus hypothesis II,e) cannot clearly be confirmed. The constraint moments changed between conditions with a trend towards a reduced load in the NS condition. However, hypothesis II,f) cannot clearly be supported by this trend. These inconsistencies can presumably also be explained by the insufficient training time.

The muscle force was greater in the WS condition for most muscles which can be interpreted that due to the shaft removal participants maintain a more neutral position and therefore less muscle force was required. Participants were not able to lean too far backward or forward in the NS condition, hence without resistance no force was produced which is in agreement with a reduced force at the patella. No changes in the forward lean above the base of support were observed. Therefore, it was assumed that the coordination and synchronisation of joint movement was changed by the skiers. As the boot shaft is often used as a lever to adjust the body position anteroposteriorly using the leg muscles, a different strategy was required to maintain balance which required less muscle activation.

The high hip compression forces of up to 128 N/kg can be explained by the GRF of approximately two times BW in addition to the great distance between the force application point and the backward leaning buttock which amounts about 30 cm at times. Further the forward leaning upper body indicated by the high hip flexion angles of up to 107° in average causes more compression the joint spanning gluteus muscles also have to work against the greatly contracted rectus femoris and iliopsoas. The GRF, the great lever arm and the muscle contraction in conjunction with higher inertial forces can lead to a potentiation of the compression forces e.g. at the hip joint as encountered in the current study. Thus concluding joints further up the kinematic chain may be more sensitive to the added boot flexibility with regard to alteration of kinetic parameters.

A potential limitation of the modified ski boot is that the removal of the shaft could reduce the balance during impact absorption due to a lack of resistance against the tibia to decelerate its forward movement which is observed in conventional ski boots. It is assumed that participants leaned back slightly in anticipation of impact due to the removal of anterior resistance. The resistance against the tibia during impact absorption would be desirable for safety. These considerations were taken into account during study III.

More in depth discussion of the computer model as utilised for the current study as well as kinematic and kinetic aspects concerning ski boot modifications will be included in the overall discussion. Important aspects of study II and III and advantages and limitations will be merged in chapter 10.

The pressure measurements that were additionally undertaken for wave slope runs and normal turns on the slope turned out to underestimate the normal forces measured during skiing. Thus this kind of measurement is not applicable to quantify forces experienced in mogul skiing, particularly if 3D data is required. The shin forces that were found to be up to 1.5 BW in extreme positions were taken into account by the model thorugh the implemented angle dependend ankle moment. The force data analysed for the intercondition comparison revealed asymmetries between the legs. Thus the measurement of medio-lateral forces became relevant for modelling input. Hence, insole measurements may be reasonable for estimations of vertical forces and sagittal plane movements such as landings, however, the requirements and accuracy for 3D analyses cannot be met.

8.6 Conclusion

In conclusion the current study successfully verified the testing process including motion analysis in an outdoor skiing environment, a rather drastic boot modification, the comparability of the force data with pressure data and the utilisation of the computer model. The movement task was simplified for this study to facilitate this verification. Performance in a wave slope is related to the vertical movements of the legs during mogul skiing. However, as mogul skiing includes turns there are presumably different joint motion and loads on the knee joint. The varying results of the current study can be explained by the lack of training time and changes in stability of the boot intervention. Additionally, the withdrawal of the shaft impedes the adjustments of joint movements by the muscle activity. Hence, further data collection was required with revised technology, sufficient training time and an improved ski boot modification.

It is critical to confirm or reject hypotheses without statistical proof. However, the focus of this study was mainly to verify the pipeline rather than evaluating the boot intervention. The results of the current study turned out to be particularly useful as another improvement loop for the force plate design was necessary prior to the final on-snow data collection. Moreover the importance of a sufficient training time to get accustomed to the modified ski boot was found to be underestimated and could be adjusted. Thus the current study provided the precondition to consider precautionary measures and ensure high quality data for the study III.

Concerning the biomechanical parameters it is important to keep noted that the current study was a test with recreational skiers on a fairly smooth slope, without turns using a drastic ski boot intervention applied as a training tool. It is the overall aim of the project to optimise equipment demands as well as performance in freestyle skiing in terms of injury prevention. Thus it still remains to be investigated if expected results as formulated as hypotheses hold true for competitive freestyle skiers using an improved ski boot modification with more posteriorly acting resistance. This will be accomplished in the following work step in study III.



Chapter 9: Study three: On mountain data collection on mogul skiing technique – improved ski boot intervention

9.1 Introduction and purpose

In the early 1990's it was shown that stiff ski boots lead to an upright or backward lean position while skiing. This may cause a loss of control leading to a potentially dangerous situation. The loss of control in the backward lean position may then lead to overloading of ligamentous structures in the knee (Hall et al., 1991) and is one of the most common injury mechanisms (chapter 2.2.3). A falling-back out-of-control posture can lead to a large quadriceps contraction to regain control which causes an anterior draw force increasing the risk of an ACL rupture.

Schaff (1993) suggested theories on non boot-induced injuries and boot-induced injury theories (Chapter 2:). Through this study Schaff (1993) coined the term "big bump flat landing" which acts as another description of the BIAD injury mechanism (Johnson et al., 1974). This is particularly meaningful for mogul skiing as highly trained skiers are more at risk for this injury (McConkey, 1986). The current study investigated a ski boot modification that is potentially applicable for the mogul skiing technique. This boot modification will allow for a greater forward lean in order to reduce the likelihood of body postures that are potentially harmful for the knee.

In the previous study the dynamics and kinetmatic parameters were investigated following a substantial ski boot modification. This modification included the removal of support in the anterior and posterior directions. This extreme intervention has been used as a balance and coordination drill for athletes previously, however it can not be used for competition or more radical manoeuvres due to potential safety issues. Furthermore, coaches and former participants of the Olympic Winter Games were concerned about its acceptance as the alterations it caused to skiing technique were too drastic (Mittermayer & Thomas, 2009). In the current study, a different ski boot modification was used which is potentially applicable for general freestyle skiing movements including mogul competition skiing. This modification has been created and discussed in correspondence with expert skiers, coaches, high-level elite athletes and technicians. It was decided that an important requirement for safety was the support in the posterior direction to be able to regain balance following overbalancing. This is common after the mandatory jumps in a mogul skiing competition. Therefore, the current study investigated a more moderate ski boot modification compared that of study II. The study has been conducted in close cooperation with mogul skiing athletes and their coaches to receive direct feedback on the equipment. The consideration of the users perspective is of importance as this is the target group of the equipment and will have implications to the future use of the equipment.

Prior to this study many smaller studies were conducted to validate the testing equipment, devices, and procedures (see Chapter 1:, Chapter 6:, 7.1.2, 8.3.6, 7.2). The on- mountain data collection of study II and III were necessary for verifying the modeling approach to calculate knee joint loading before and after the ski boot intervention. The goal of the study was to optimise equipment demands and performance in freestyle skiing. The research question was if the modified ski boot can aid in reducing knee joint loading during mogul skiing and whether it is potentially applicable for a competition situation. As mentioned previously the overall discussion (Chapter 10:) will merge the results of the ski boot intervention studies (II and III) and will provide conclusions for athletes, manufacturers and the general freestyle skiing population.

9.2 Hypotheses

| Hypothesis III.a): | Maximal ankle flexion angles will be greater in the modified ski boot. |
|--------------------|---|
| Hypothesis III.b): | Participants will be able to ski with a significantly greater forward lean of the body's CoM after the intervention. |
| Hypothesis III.c): | Following a three day familiarization period, participants will not feel negative impacts caused by the ski boot modifications. |
| Hypothesis III.d): | Measured GRF will be reduced when wearing the modified boots. |
| Hypothesis III.e): | Net joint forces and moments on the knee will be reduced when wearing the modified boots. |
| Hypothesis III.f): | Simulated muscle activation of the vasti will be reduced after the intervention. |
| Hypothesis III.g): | Simulated muscle activation of the hamstrings will be reduced after the intervention. |

9.3 Methods

Most components of the methods in this study were identical to study II. Therefore, the list for the general equipment needed and specifications for the kinematic and kinetic data collection can be located in the methods section of study II (chapter 8.3).

9.3.1 Subjects

Nine male elite mogul skiers (20.9 \pm 6.92 yr) of the German national freestyle team participated in the study (Table 17). Semi-professional mogul skiers were chosen as participants for this study because the aim was to gather data from steady and highly skilled performances. All participants completed a general questionnaire that screened for contraindications (appendix 3). Ethical approval was granted by the University of Auckland Human Participants Ethics Committee (Ref 2007/106). A previously conducted study found a low variability between and within subjects at a high elite level (Schaff, 1995). The author believed that consequently a lower sample size may suffice for investigations on such a target group. This may hold true for the current study.

| Participant [n=9] | Age [years] | Gender[M/F] | Body height [cm] | Body weight[kg] |
|-------------------|-------------|-------------|------------------|-----------------|
| Mean | 20.9 | М | 175.9 | 66.7 |
| SD | 6.92 | | 7.30 | 11.27 |

Table 17: Anthropometrics of participants if study III.

9.3.2 Ski boot modification

An expert level ski boot was modified for the study (Head Raptor Super Shape, Head Inc., USA). The ski boot's shaft was removed and the residual material in the anterior and posterior direction was cut at the instep before the shaft was refitted (as shown in Figure 78). However, in order to gain a noticeably greater ankle flexion, only two screws per boot were used to fix the shaft at the pivot points of the lateral and medial malleolus. The buckle of the shaft and the rigid proportion of the instep of the boot continued to serve as a block and restricted the forward lean in an extreme position. To ensure the durability of the plastic around the pivot points and to prevent breakages, small aluminium plates were manufactured to reinforce the screw holes inside the boot and outside the shaft. The modification was applied to three pairs of the same ski boot model in different sizes (28.0, 28.5, 29.0).



Figure 78: Modified ski boot with reduced plastic and one pivot point at the ankle joint.

9.3.3 Test protocol overview

This field test was conducted at the Zugspitze ski field in Germany. All participants received a modified ski boot for three days training as familiarisation period.

On the day of testing all participants warmed up, as required. This was performed on the normal slope and five runs of the mogul course, with instructions to practice correct mogul technique. After all necessary preparations (such as marker attachments and force plate adjustments) the subjects were tested for three consecutive runs with the modified ski boots (Figure 79). Following this, they swapped to the normal ski boots and performed a second set of three runs (Figure 55).



Figure 79: Participant during testing in mogul slope.

The kinetic data acquisition was described in the previous chapter (chapter 8.3.7) as it was identical with study II (Figure 55). The subjects used their own skis, as they have different preferences and altering these can influence the performance (Raschner, 1997). In study II recreational skiers were tested. These subjects had no specific preferences for the type skis and therefore one pair of skis was appropriate for all participants.

The weather conditions were stable on the chosen testing days as the temperature ranged between 0 and -5° Celsius. The testing course had an inclination of 25° and was situated at an altitude of 2500 m. The moguls had a distance of approximately 4 m from each other and the relevant measurement area measured approximately 3 m by 10 m. The mogul course consisted of ten moguls. Moguls number five and six were the relevant moguls for data acquisition so that all participants had sufficient time to create their velocity and rhythm. The turns were defined as a right and a left turn as the first impact occurred on the right side and the second impact on the left side following an immediate change of direction respectively (Figure 80).



Figure 80: Schematic of camera setup and line of travel.

9.3.4 Data collection

The mobile high speed video system (Simi Motion, Germany) was set up with five cameras on elevated hills around the testing area and recorded at 100 Hz. The cameras had a resolution of 656×490 pixels and were positioned at a distance of five to eight meters at either side of the testing area. This was to ensure an angle between any two optical axes of about 60 to 90 degrees (Figure 80).



Figure 81: Testing slope, downhill view with three (out of five) visible cameras elevated on snow hills.

The kinematic measurement equipment and devices were the same as those used in study II except that five cameras were used. In this instance, a power station was available so that there was no need for a generator (chapter 8.3.3). Testing took place within a fenced area that was not accessible to the general public to ensure the conditions were kept constant. However, due to snow fall during the two testing weeks this could not be accomplished for all testing sessions, but the investigators re-arranged the moguls to the original set up. The conditions for the intra subject comparison (two ski boot conditions per participant) were constant as these were performed on the same day.

A set of 19 black markers (plus eight static markers) with a diameter of 40 mm were fixed to the skier bilaterally on the bony landmarks. Figure 38 and Figure 61 of the previous chapters and the associated lists illustrate the exact marker placement. These were affixed with adhesive tape to a yellow racing suit worn by the participants.

After the third training day all participants completed a second questionnaire addressing their perception of performance in the FL condition compared to the ST condition. The items on the perception questionnaire were selected and considered relevant for mogul skiing performance by the main investigator in cooperation with a former world class freestyle coach from New Zealand (Harrington, 2008). These aspects related to shock absorption, forward lean, edging, balance, speed control, safety, overall acceptance as a training tool (e.g. balance training) and overall acceptance as a competition ski boot. This

questionnaire was the same as the questionnaire used in study I (chapter 5.3.4, Figure 36). The procedures of testing were the same as study II and is summarised in Figure 55. The questionnaire is attached as appendix 5.

For acquisition of kinetic data the same force plate with the same adjustments as study II was utilised (Figure 58, Figure 82).



Figure 82: Kinetic measurement equipment (two ski force plates, data logger, sync trigger, pressure measurement system for different study).

The same technique was used for kinematic calibration as in studies I and II, except eight pole positions were used instead of twelve (study I) or six (study II) (chapter 5.3.5, Figure 83).



Figure 83: Testing slope with theodolite and calibration pole for kinematic calibration.

9.3.5 Data analysis

A total of six trials were recorded per participant (three trials per condition). This totalled 50 trials since some trials were discarded due to poor camera adjustments. The trials were considered to be usable if snow contact was maintained, the upper body was kept still and there was appropriate bending and straightening of the legs. These criteria were selected by the main investigator in co-operation with the former New Zealand national freestyle coach (Harrington, 2008).

The data analysis procedures including the implementation of the model were identical to study II except for the different ski boot stiffness values (chapter 7.2.3). According to the stiffness tests three different adjustments were defined, specifically 'no shaft' (study II, without added stiffness), 'Flex' (FL) and 'Standard' (ST) which were adjusted manually to the appropriate trials. A joint moment was incorporated into the ankle joint definitions of the model. This varied depended on the joint angle. Figure 84 provides a graphical presentation of the investigated kinematic parameters. Additionally, the side lean of the CoM in relation to the force plates have been measured. It was defined similarly to the forward lean in Figure 84 as the difference of the CoM position and the point halfway between the bindings in a plane defined by the vertical and the CoM direction seen from above.



Figure 84: [modified from Kassat (2000)]: Graphical illustration of kinematic parameters investigated (KA = knee angle, HA = hip angle, CoMdir = path of the body's centre of mass, CoMdist = horizontal distance of CoM and a point halfway between both ankle joint centres, AA = ankle angle)

9.3.6 Statistics

Data were tested for normality using the Kolmogorov-Smirnov test. If normality was rejected, the Wilcoxon signed ranks test was used. Otherwise, a paired t-test was used to test for differences between the 'modified' and the 'normal' condition using a Student Newman-Keuls test for post hoc comparison. Significance was set to < 0.05. All data were analysed using NCSS 2000. Results

9.4 Results

9.4.1 Perception

The data of one participant was discarded due to the poor quality of the videos. Hence, the data of eight participants was included for analysis. Figure 85 displays the mean and standard deviation (SD) for the eight ratings regarding the skiers' perception of their performance with the FL condition compared to the ST condition. The only items that the modified ski boot is rated lower for than the normal boot are balance and speed control, however, these were non-significant (Figure 85). The rating for edging and for acceptance as a competition boot are slightly higher for FL than for the ST condition. For the remaining items the modified flexible ski boot was rated significantly higher than the standard boot (p=0.006 for absorbing, p=0.005 for forward lean, p=0.01 for safety, p=0.01 for acceptance as a training tool).



Figure 85: Participants' perception of the modified flex ski boot (condition FL) compared to their standard ski boot (condition ST) on selected aspects of skiing. 5=no difference, negative=worse, positive=better, *=significance at p<0.05.

9.4.2 Kinematics

Kinematic parameters showed large changes for maximum ankle flexion angle, which increased from the ST to the FL condition from 16.3° and 13.2° to 22.7° and 18° (right/left) (Figure 86). The only significant kinematic alteration between the conditions occurred for the minimum ankle flexion on the right side (p=0.037). This contributed to the reduced range of movement in the ankle joint of approximately 7-14%.



Figure 86: Averages of maximum and minimum ankle flexion angles. Significance at p=0.05.

The maximum knee flexion angle was increased in the FL condition with 87° and 83° compared to 81° and 77° (right/ left) (Figure 87). The range of movement was about 10% greater in the FL conditions for both legs.



Figure 87: Average of maximum and minimum knee flexion angles.

The hip flexion angles remained unchanged with same range of movement in both conditions for both sides (Figure 88).





The anterio-posterior position of the CoM remained unchanged for both conditions with a slightly greater movement range of 37 cm compared to 34 cm in the FL condition. This change of position, above the base of support, while absorbing the bumps, is displayed in Figure 89,a) for participant 1. The same holds true for the side lean, which does in average not notably change between conditions with 24 cm and 25 cm, however, the range is slightly but not significantly greater in the FL condition (Figure 89,b). The positive values describe the CoM leaning towards the left side and negative values towards the right side.





Figure 89: Illustration for participant 1 for one turn for a) the anteroposterior movement of the CoM in relation to a point half way between both ankle joint centres, b) the side lean of the CoM in relation to a point between both ankle joint centres.

9.4.3 Kinetics

Kinetic parameters demonstrate a greater change than the kinematic parameters between conditions. The ankle compression force was between 24% and 53% lower for the ST to the FL condition. The ankle extension moment changed about 35% on both sides from - 2.23 Nm/kg/m and -3.2 Nm/kg/m to -1.37 Nm/kg/m and -1.97 Nm/kg/m (Figure 90).



Figure 90: Average ankle flexion-extension net moments in the FL and ST condition. Negative=extension.

The anteroposterior knee joint force was 27% and 19% reduced between conditions from - 62.77 N/kg and -57.01 N/kg to -46.19 N/kg and -46.64 N/kg (Figure 91,a). The knee compression force had a trend towards being lower in the FL condition with a 22% to 17% decrease from 90 N/kg and 85 N/kg to 71.18 N/kg and 71.69 N/kg (Figure 90,b). However this difference was non-significant. The average of both sides of the femoro-patellar compression force remained unchanged at approximately -100 N/kg on the right and approximately -65 N/kg on the left side (Figure 91,c).





Figure 91: Average of minimum and maximum net knee force, a) anteroposterior force, b) compression force, c) femoro-patellar compression force.

The knee flexion moment demonstrated a significant reduction of approximately 50% and 33% from 0.89 Nm/kg/m and 1.11 Nm/kg/m (p=0.013) to 0.45 Nm/kg/m and 0.75 Nm/kg/m (right/ left) from the ST to the FL condition. However, the magnitude of the knee extension moment demonstrated the opposite trend with an 90% to 190% increase from -0.53 Nm/kg/m and -0.23 Nm/kg/m to -1.03 Nm/kg/m and -0.67 Nm/kg/m (Figure 92,a). The knee internal-external rotation moment, describing the internal-external rotation, increased for right and left sides in the FL condition from 0.17 Nm/kg/m and 0.65 Nm/kg/m to 0.27 Nm/kg/m and 0.92 Nm/kg/m with a significant difference on the left side (p=0.02) (Figure 92,b). The lateral knee moment, representing the varus-valgus moment was 23% larger on the right side and 10% lower on the left side for valgus in the FL condition with 0.55 Nm/kg/m and 0.20 Nm/kg/m from 0.44 Nm/kg/m and 0.22 Nm/kg/m. The varus moment remained the same on the right knee around -0.2 Nm/kg/m and increased about 23% in FL for the left knee from -0.43 Nm/kg/m to -0.53 Nm/kg/m (Figure 92,c).



Figure 92: Average knee joint moments in the FL and ST condition for a) flexion-extension moment, b) internal-external rotation moment, c) lateral moment. Sign. level *p*=0.05.

The hip compression forces added to 167 N/kg and 148 N/kg in the ST condition and were reduced by 23% and 10% in the FL condition to 129 N/kg and 133 N/kg (Figure 93).



Figure 93: Averages of hip compression force in FL and ST condition.

The vertical GRF remained the same with only slight changes of 3% to 5% around 10.2 N/kg on either side on average.

9.4.4 Muscle activation

The muscle activation of the lower limb muscles, such as soleus and gastrocnemius muscles, had a 37% and 50% greater activation in the ST condition. The soleus demonstrates forces between 31.28 N/kg and 39.71 N/kg for FL compared to 19.89 N/kg/m and 24.82 N/kg/m in the ST condition. The gastrocnemius group showed larger differences of 50% to 60% with a reduction from 5.43 N/kg and 7.98 N/kg to 2.34 N/kg and 3.95 N/kg (Figure 94).



Figure 94: Average muscle activation at the lower limb, a) soleus, b) gastrocnemius (RSolM=right soleus medialis, RGastL=right gastrocnemius lateralis, RGastM.=right gastrocnemius medialis).

The vasti muscle activation remained unchanged with a slight reduction in the FL condition for the vastus lateralis of 4% to 14% from 11.41 N/kg and 11.29 N/kg to 10.98 N/kg and 9.72 N/kg (Figure 95,a). The rectus femoris showed no changes. The hamstrings demonstrated a greater activation level in the ST condition with 24.6 N/kg and 26.51 N/kg compared to 14.85 N/kg and 19.87 N/kg in the FL condition (Figure 95,b).



Figure 95: Average muscle activation of a) vasti muscle group, b) rectus femoris and hamstrings (RRect.=right rectus femoris, RHam.=right hamstrings).

The ratio of flexor: extensor activation did not change between conditions and was 0.73 and 0.82 in the FL condition and 0.9 and 1.07 in the ST condition.

9.5 Discussion

The current study was designed to investigate knee joint loading following a modification to the design of the ski boots in mogul skiing. Results demonstrate acceptance of the modified ski boot by semi-professional freestyle skiers. Kinematic parameters showed slight alterations in the FL condition, whereas differences in kinetics were more obvious. Muscle activation was generally larger in the ST condition for all investigated muscles. The perception ratings showed that the modified ski boot was accepted by highly skilled mogul skiers. Most participants stated initial doubts about the comfort with the modified ski boot with respect to the control boot for the parameter of balance and therefore they were concerned about their safety. However, following three days of familiarisation all participants became accustomed to the new boot. Despite persisting doubts for factors such as 'balance' and 'speed control' ratings on the acceptance of the modified ski boot were generally positive. The evaluation of the modified ski boot was better than for the conventional boot for six out of eight items, significantly better for four items and slightly worse for two items (Figure 85). Hence, hypothesis III.c) can be confirmed.

Mogul skiing technique was adjusted by the participants of the current study so to use a greater ski boot flexibility. This is shown in Figure 96 for a single participant's hip flexion angle.







Figure 96: Hip flexion angle of a single trial comparing FL and ST condition, a) right side, b) left side.

It can be observed that a greater range of movement in both flexion and extension occurs. Approximately 10° of hip flexion-extension was gained and corresponded to a better knee range of motion (of approximately 9° to 12°) and a greater maximum ankle flexion angle of 5° to 6° . This can contribute an increased absorption of the forces while skiing (Figure 97). A more distinct alteration of ankle joint flexion was expected since the modified boots' flexibility was 1.6 times greater than normal. Hypothesis III,a) must be rejected. However, the right ankle flexion minimum and the ankle range of movement were significantly larger in the FL condition (p=0.037, p=0.022).




Figure 97: Knee flexion angle of a single trial comparing FL and ST condition, a) right side, b) left side.

The greatest GRF and the greatest joint angles were inversely proportional. Thus, during the main impact the ankle, knee and hip joints reached the smallest angles as proposed by Arndt (1994) which is a main characteristic of mogul skiing.



Figure 98: GRF plotted against knee angles for a right turn of participant 1.

This posture potentially exposes the joints and ligaments to a greater risk of injury if a neutral position cannot be maintained (Chaudhari & Andriacchi, 2006). The changes in GRF were negligible but showed a slight tendency to decrease in the FL condition so hypothesis III,d) is rejected.

The specific ACL load could not be calculated by this model, but axial net knee forces decreased between 27% and 19% between conditions from -62.77 N/kg and -57.01 N/kg to -46.19 N/kg and -46.64 N/kg. It can be assumed that ACL loads were reduced by about the same percentage. The highest peak anterio-posterior force at the knee was measured for participant 4 at approximately 215.66 N/kg (13 000 N) in the ST condition. These high forces can be explained by the contribution of the muscle, accounted for in the current model, which makes it impossible to compare these values with the calculated values without muscle contribution.

The differences between the conditions are large at peak force. While the CoM demonstrated no differences between conditions over the runs, there was an anterior shift of 5 cm when peak forces were acting at the sole of the ski boots in the FL condition. This alteration of body posture supports hypothesis II,b), although it is non-significant. The vasti muscles were in average 1-14% more activated in the ST condition and 17-22% at instant of peak force, which is a trend but does not confirm hypothesis III,f) since it is

non-significant. As hamstring muscle activation had a trend to an increase in the ST condition and at peak force hypothesis III,g) is rejected. The left leg showed a flexorextensor ratio of 0.5 in the FL condition compared to a 0.41 ratio in the ST condition. This is a minor change comparing the conditions at this specific point in time, but a large change comparing it to the average ratio over the runs which was 0.7 and 0.8 in FL and 0.9 and 1 in ST. This increased ratio of hamstring activation in relation to the quadriceps activation means there is probably a greater protective effect to the ACL. There was a significant reduction of the anteroposterior tibial force of 30% at the instant of peak force when compared to the ST condition which supports this trend and confirms hypothesis III,e). This is in line with a 30% reduction of the femoro-patellar compression forces that further back up this trend.

A 30 cm backward lean of the CoM as observed in the current study cannot be kept stable without additional support as known from weight lifting (Wretenberg, Feng, & Arborelius, 1996). Thus, apart from inertia and a dynamic balance the influence of the stiff rear spoiler of the ski boot is still assumed to be large enough to keep the CoM stable during the squatting movement in mogul skiing. Using the rear spoiler as the resistance to push the CoM to a neutral position requires muscle activation of the quadriceps muscles which is not significantly different between conditions. The increased anterior flexibility tends to elicit a better maintenance of the neutral position and thereby lowers the risk of getting into a backward position. This is in agreement with the participants' comments on the questionnaire and can be confirmed by the analysis of the GRF's that regularly turned to zero or negative from peak values and showed an additional smaller peak when clearing the mogul in the ST condition. This indicates a slingshot effect which is an unintentional take off due to inappropriate absorption. In the FL condition skiers managed to maintain better snow contact (Figure 99). The greater quadriceps muscle activation supports this explanation.





Although the initial analysis of the data suggests only minor beneficial effects in the FL condition for the average values over the runs, at the instant of maximum force all kinetic values turned out to be reduced. This is due to a change in the kinematic strategy with the CoM in a greater forward lean. This in turn is assumed to result in a more agile absorption movement with more range of movement of the CoM in posterior direction to attenuate the impact more gently and with an increased range of movement in the knee joints. The findings of the current study will be discussed with the literature in chapter 10.

9.6 Conclusion

The current study revealed that knee joint loading can be reduced using a more flexible ski boot with three days of training using the modified boot.

The modifications to the ski boot made in the current study could be used as a prototype for future ski boots as it has the desirable ski boot characteristic with regard to flexibility and safety. As these results are promising it is recommended that these adjustments are incorporated into the design of ski boots. However, such a ski boot modification for regular production may require other adjustments to equipment such as bindings, their release values or skis.

Chapter 10: General discussion

The major goal of the current project was to investigate joint loading conditions during freestyle skiing and how the possibility of injury can be altered following ski boot modifications. The idea behind the thesis was to reduce knee joint loading by the employment of a modified ski boot that allows for a significantly greater ankle flexion. The boot should align the body's CoM over the base of support in order to reduce lever arms and the strain on the knee. This will enable skiers to absorb the impact of the moguls with less backward lean which will consequently reduce the strain in the knee joints.

Three consecutive studies were conducted each based on the findings of the previous study to progressively accomplish a data base for a computer modelling approach. The previous chapters encompass an extensive literature review, several validation studies and the planning and implementation of the three main studies as well as the processing of all data. This chapter will eventually merge the results for an overall discussion. This discussion summarises these findings and relate them to existing literature. Aspects of computer modelling and the method used in the current study explaining the advantages and disadvantages will be discussed.

10.1 Comparison with mogul skiing literature

In this section, the current data will be compared to the limited literature on mogul skiing. A study on a task similar to study II of the current project used a stiff ski boot (SB) and a commercially available soft (more flexible) boot (FB). Test runs in a wave slope were investigated and the project was sub-divided into the analysis of kinematic and kinetic parameters (Kampe, 2008), the emphasis on muscle activation analysis (Machens, 2006) and the development and evaluation of two different musculoskeletal computer models (Friedl, 2007). This project reported similar results to the current project, however, some differences were also observed. Machens (2006) reported minimal differences in the intercondition joint angle means. Similarly to the current study II this could be due to a relatively short period of familiarization of only four hours. As explained in chapter 8.5 this is potentially problematic for movement tasks that are similar to movements that have been learned and automatised. The engram in the brain has to alter the known "movement program" (Monfils, Plautz, & Kleim, 2005) which can be challenging depending on the difficulty level of the task and may require a sufficient training period to alter. However,

the range of ankle movement for individual participants in the NS condition in study II was approximately seven degrees greater than the Machens' study with 20° compared to 13°. This was primarily due to increased maximum extension angle indicating a more active leg extension behind the bump as it is crucial for speed and balance control in mogul skiing. The knee angles were greater in the current study in the extension directions but not in flexion. This could be explained by possible differences in the initial joint angle definitions since the range of movement is similar in both studies. The hip angles showed a greater range of movement towards the upright position in the current study III.

Another difference could be revealed due to the analysis of kinetic parameters such as GRF which were reduced in study II from the WS to the NS condition from approximately 2600 N maximum to 2400 N maximum for both legs (average from 2350 N to 2150 N). By contrast, Friedl (2007) reported an increase from 2800 N to approximately 5000 N from the SB to the FB condition with the same task and a similar test course setup (bump height 1 m, "medium" inclination without specific indication). However, the authors assumed that this is measurement error that was elicited by the use of a muscle moment driver for the soft boot (Friedl, 2007). While the knee net moments for flexion-extension were lower in the current study for the normal boot this difference persisted for the FB and NS condition with 400 Nm measured by Friedl versus approximately 240 Nm in study II as peak values. Interestingly the changes were different for study III with a greater decrease of the normal force from approximately 2800 N to 2000 N and 230 Nm knee flexion moment in the ST condition to approximately 130 Nm with the modified boot. Study III was the only study including mogul skiing technique with turns which is assumed to have effects on the kinematic strategy to absorb the forces. Table 18 represents selected parameters of the current project in comparison with Friedl, Machens and Kampe.

Table 18: Comparison of selected parameters of the current project with a preceding project (data set used by Friedl, Machens and Kampe, indicated here representatively as Machens). The indicated angles are displayed as minimum/ maximum average values [ranges] for individuals for the flexible boot (FB), stiff boot (SB), non-shaft (NS), with shaft (WS), flexible (FL) and standard (ST) conditions.

| PARAMETER | MACHENS STUDY | | CURRENT STUDY II | | CURRENT STUDY III | |
|---------------------------------|----------------|----------------|------------------|----------------|-------------------|----------------|
| | FB | SB | NS | WS | FL | ST |
| Ankle angle [deg] | 12/25 [13] | 8/25 [17] | -5/20 [20] | -8/12 [20] | -6.6/30 [36.6] | -13/29 [42] |
| Knee angle [deg] | 52/115 [63] | 52/103 [51] | 32/86 [54] | 32/84 [52] | 33/106 [73] | 21/103 [82] |
| Hip angle [deg] | 35/132 [97] | 35/130 [95] | 38/102 [64] | 40/107 [67] | 23/112 [89] | 19/113 [94] |
| GRF_sum [N] | ≈ 5000 | ≈ 2800 | ≈ 2400 | ≈ 2600 | ≈2000 | ≈2800 |
| Knee net flexion moment [Nm] | ≈400 | ≈270 | ≈240 | ≈200 | ≈130 | ≈200 |

Machens' focus was the analysis of the muscle activation patterns of the same muscles as derived from the model in the current project. The author reported an extensive raise in the muscle activation of 30% to 80% for all muscles in the FB condition. This could be explained by a more active involvement of the muscles for the bending and straightening action due to a lack of resistance at the ankle joint. However, this finding does not correspond with the results of study II and III where most muscles were more activated with the stiff boot compared to the soft boot. The voluntarily activated maximum force, as tested prior to the field tests, exceeded in the FB test runs. The muscle activation peaks were greater on the second bump (Machens, 2006). This was theoretically more likely to occur in the WS condition in study II as this condition exhibited the greater muscle activation in general. Despite this, a maximum force test and a distinction between the first and the second bump have not been conducted in the current project. Another possibility is that wearing ski boots may inflict some gross change in motor control. It has to be noted that the muscle activations here are model based on a force minimization optimization criterion. It can, therefore, not be concluded which of the two possibilities applies.

For the comparison of Machens (2006) with the current results the results of study II and study III must be distinguished as they used slightly different methods and, most importantly, different ski boot modifications. A comparison of Machens' (2006) project

with the current project show similarities and differences from study II and III. Although both projects were aiming at modifications of the positioning on the ski depended on ski boot stiffness, there are several differences in the measurements that led to these distinctions. For instance, Kampe and colleagues used a commercially available soft boot which is not available on the market anymore due to a lack of demand. The current project used a boot without a shaft in the first intervention and secondly a custom-made boot modification that allowed for significantly more ankle flexion, but ensured normal stability posteriorly and medio-laterally (chapters 8.3.3, 9.3.2). According to the participants, this stability was important to ensure a feeling of safety and not compromise confidence when absorbing moguls at higher speeds. This stability was not assessed in the above project (Machens, 2006).

The setup of the current project was more comprehensive with five (four in study II) cameras as to ensure the most possible precision for a 3D movement reconstruction. Therefore, 27 markers of 40 mm diameter were attached to a race suit as opposed to a reduced marker set with bigger markers on normal skiing clothes (Figure 100). No indication of the size of the markers was given.



Figure 100: Illustration of different markers attached to the participants for a) Machens/ Kampe/ Friedl project, b) the current project study III.

Additionally, the current project included a marker movement study to estimate the degree of imprecision due to skin artifacts that is assumed to be slightly lower with a race suit compared to skin based markers (chapter 6.2), but better compared to wide skiing clothes.

Another difference between the projects is that Machens (2006) had one data collection for several investigations whereas in the current project another data collection for study III has been conducted for which a few substantial advancements were implemented. For instance, the wave slope experience became extended to a real mogul skiing course. The training time for familiarisation to equipment was three days. It was assumed that some participants in Machen's (2006) study did not utilise the new flexibility due to the lack of training time. They might have been afraid of hurting themselves due to the extensive flexibility as they had no block in the anterior direction. This was not given for the intervention in study II, however for the more advanced study III with a more skillful performance execution, this aspect has been considered and implemented. Thus, there are several aspects to consider that can influence the results. Differences in measurements can be encountered due to differences in the initial position of the model, the height of the moguls or the inclination of the testing slope. Regarding joint angles, some researchers determined zero in the static trial when the participant is already in a slightly flexed position and other researchers determine an upright position without boots as the 0° or 180° (McAlpine, 2006). Other aspects that lead to differences in results of the two projects are camera adjustments, methods for digitisation, accuracy of the force plates, calculation matrix for the GRF, the choice of the model and the model specifications. The two projects did not attain the same findings regarding knee joint loadings in freestyle mogul skiing. Friedl (2007) stated that only limited conclusions could be drawn based on their findings due to a lack of precision and measuring errors for joint moment values. The methodological differences need to be considered for the interpretation of the current results.

Previously, it has been stated that knee joint loading in mogul skiing can be reduced by 35% using a more flexible ski boot (Schaff & Olbert, 1996). The authors stated that the reduction of heel pressure of approximately 35% caused the reduction of knee joint loading of the same amount. They proposed that a comprehensive 3D motion analysis was required to further explore knee joint loading in mogul skiing. The results of study III did not reveal many changes over the run, but they demonstrated a significant decrease in joint loading at the instant of peak force. Figure 101 is an example of a 170% larger joint loading in the ST condition when an identical amount of peak normal GRF was applied. This outcome corresponds with a greater forward lean causing a more advantageous body



posture with respect to knee joint loading and a reduced femoro-patellar compression force.



Figure 101: Example for the slope of GRF with indications for anterio-posterior knee joint loading at force maximum in the FL and ST condition for a single leg (participant 3) (ap=anterior-posterior).

Although the knee joint loading reduction was not as large as predicted, the results are in accordance with Schaff and Olbert (1996).

The comparison of these studies suggests that outcome measures are particularly depend on several methodological specifications. An addition, almost significant differences in joint loading elicited by the modified boot were revealed, suggesting the chosen intervention can have beneficial effects on freestyle skiing biomechanics. Study III is unique and there is no similar study available for comparison. The results will be discussed in the following sub chapters in the context with other skiing disciplines.

10.2 Comparison with general skiing literature

It is proposed that alpine skiing has a higher risk of ACL injury than any other sport (Urabe et al., 2008). GRF values of two times BW in a wave and mogul slope with moderate inclination and speed seem realistic as Lafontaine (1998) reported to three times BW for carved turns. In the current study, loads were more unevenly distributed than for carved and skidded turns as listed in Table 19 which indicates a fundamental difference in technique. Klous (2007) measured two times higher normal force on the outside leg

compared to the inside leg for skidded and carved turns with up to 1.18 BW for carved turns. Similar values in skiing were measured previously (Maxwell & Hull, 1989b; Niessen et al., 1999; Raschner et al., 1999). The measured normal GRF was higher in mogul skiing with 1.5 BW to 2 BW, but no major differences towards a greater outside leg loading were observed. On contrary, the FL condition in study III exhibited about 17% and and the ST condition 5% higher average GRF on the inside leg compared to the outside leg. This can be explained by the positioning of the skier with respect to the mogul and thus on a continuously and in all directions changing surface inclination. Furthermore, the inside leg is closer to the mogul at the instant of impact and when skidding down on the backside of the mogul just before extending the legs and changing the edge. Values for the anteroposterior moment in both conditions of the current study compare well with Klous' CA (carving) condition (Table 19). The same holds true for Klous' SK condition on the outside leg. All other parameters exhibit notably larger values for mogul skiing in both conditions, however, they do not differ between conditions. This can be explained by a more pronounced side lean in skidded and carved turns with a more open position on the ski with the weight on the outside leg, whereas in mogul skiing a closer leg position is common to evenly distribute the weight and maintain balance. The vertical peak forces measured by Klous amounted 3.63 BW for both legs compared to 4.89 BW as measured for participant 4 in a mogul run in the ST condition.

Table 19: Comparison of GRF and associated moments of the current project with other skiing disciplines. The values in this table are displayed as average values for outside/inside leg. Different conditions in the respective studies are skidded turns (SK), carved turns (CA), moguls in current project with flexible boot (FL) and for the standard boot (ST) condition. Fx= anterio-posterior force, Fy.= medio-lateral force, Fz=normal force.

| | Klous (2007) | Klous (2007) | | Current study III | |
|------------|--------------|--------------|------------|-------------------|--|
| | SK | CA | FL | ST | |
| Fx (N/BW) | -0.04/-0.02 | -0.02/-0.02 | 0.21/0.23 | 0.3/0.3 | |
| Fy (N/BW) | -0.05/-0.03 | -0.03/-0.02 | 0.19/-0.17 | 0.2/0.25 | |
| Fz (N/BW) | 0.95/0.56 | 1.18/0.55 | 1.73/1.69 | 1.77/1.76 | |
| Mx (Nm/kg) | 0.17.0.09 | 0.18/0.09 | 0.37/0.33 | 0.38/0.30 | |
| My (Nm/kg) | 0.42/0.60 | 0.25/0.49 | 0.35/0.49 | 0.45/0.47 | |
| Mz (Nm/kg) | 0.10/0.05 | 0.18/0 | 0.13/0.26 | 0.11/0.16 | |

These insights lead to the conclusion that the proximal-distal and anteroposterior adjustments in mogul skiing are more important over medio-lateral adjustments. This is supported by the greater anteroposterior forces in the current study and a minor range of medio-lateral movement of the CoM with 25 cm in both conditions as compared to approximately 60 cm to 80 cm as found by Raschner et al. (2001) for parallel turns. Therefore, the conclusions from other skiing disciplines are not applicable for mogul skiing due to the substantially different nature of the technical execution.

Knee angles and the measured GRF in the current study were similar to Raschner's (1999) analysis of giant slalom (GS) turns. However, both knee angles and GRF were more unevenly distributed in GS. A world champion in GS exhibited maximum forces of 1 557 N on a single leg and loaded the outside leg more on the forefoot whereas the inside leg was more loaded on the heel. The knee angle was greatest on the inside leg with approximately 100° with simultaneously acting peak forces. The smallest extension angle was approximately 50° in the initiation phase of the turn. The scenario in mogul skiing showed the same values in the opposite order, with the smallest knee angles of approximately 50° at peak impact, and up to 106° knee angle (for participant 7) when clearing the mogul. For mogul turns no differentiation has been made for the anterioposterior pressure distribution for each leg or a possibly the varying force application point. However, the relatively evenly distributed GRF in conjunction with similar knee angles lead to the assumption of similarly distributed loads at the foot. An anterioposterior shift of the CoM of approximately 10 cm in high elite GS compared to a range of 37 cm (on average) with values of up to 50 cm for a single participant (no. 7). This further supports a distinct difference in the fundamental movement patterns of these disciplines.

Generally, for comparison of knee joint forces and moments, parameters have to be calculated within the same coordinate system. Significant differences have been reported for the calculation of joint forces and moments using different coordinate systems (Liu & Lockhart, 2006; Manal et al., 2002; Schache & Baker, 2007). Previously, several studies used the local coordinate system of the tibia to calculate knee joint forces in ski jumps and turns (Herzog et al., 1993; Maxwell & Hull, 1989a; Nachbauer & Kaps, 1996; Read & Herzog, 1992). This calculation method has been adapted for the current study. Average forces and moments at the knee joint are displayed in Table 20 with values calculated by Klous.

Table 20: Knee joint forces and moments for each component of the current studies compared to Klous (2007) in carved and skidded turns. Indications are given for outside/inside.SK=skidded turns, CA=carved turns, NS=no shaft condition, WS=with shaft condition, FL=Flex condition, ST=Standard condition. Fx=anteroposterior force, Fy=compression force, Fz=medio-lateral force, Mx=lateral moment, My=internal-external rotation moment, Mz=flexion-extension.

| | Klous (2007) | | Current study III | |
|------------|--------------|-------------|-------------------|--------------|
| | SK | CA | FL | ST |
| Fx (N/BW) | 0.21/0.20 | 0.47/0.21 | -8.0/-8.04 | -11.0/-10.14 |
| Fy (N/BW) | -0.70/-0.56 | -1.07/-0.52 | 12.02/12.09 | 15.27/14.44 |
| Fz (N/BW) | -0.56/0.12 | -0.09/0.05 | - | - |
| Mx (Nm/kg) | 1.30/-0.36 | 1.07/-0.89 | 0.96/-0.94 | 0.76/-0.75 |
| My (Nm/kg) | 0.99/-0.29 | 0.51/-0.28 | -1.6/1.58 | 1.75/1.19 |
| Mz (Nm/kg) | -1.89/-1.11 | 0.34/-0.53 | -1.82/-1.21 | -0.99/-0.5 |

In the current study, joint forces calculated by the model were larger due to the incorporation of muscles in the model which were not accounted for by Klous (2007). Anteroposterior forces at the knee reached 11 BW in the ST condition of study III and were reduced to 8 BW in the FL condition. The compression forces were the highest in the ST condition and showed approximately the same amount of reduction in the FL condition. The comparison between the studies demonstrates relative differences in GRF's and calculated net forces. Thus, knee compression forces on the outside leg were approximately 25% higher in skidded turns and 50% higher in carved turns whereas they were evenly distributed in both mogul skiing conditions. The net moments can be compared and are, on average, similar in the FL and SK conditions for flexion and lateral moments and are greater in carved turns compared to the current ST condition. The average internal-external rotation moments are higher in both mogul skiing conditions than in skidded and carved turns. This can be explained by higher impacts in conjunction with small turns that are maximal 4 m in length. Analysis of the peak values reveals a substantially different trend. Klous calculated peak lateral knee moments of up to 5.7 Nm/kg which are outstandingly high compared to maximum peaks of 3.4 Nm/kg in the FL condition in study III. The peak flexion moments were higher with 8.35 Nm/kg compared to 3.8 Nm/kg for participant 4 in study III in the ST condition. The internal-external rotation moment in Klous' study reached 6.85 Nm/kg versus 4.61 Nm/kg for participant 7 of study III in the ST condition. It can be assumed that a different edging technique in

mogul skiiers can cause different knee joint moments. In mogul skiing the 'block' position is required with the feet close together and the weight evenly distributed which distinguishes mogul skiing from carving. The changes of direction and joint angles in carved turns result in a smoother trajectory of the whole body with controlled edging in a shoulder wide position on the skis (Raschner et al., 1999). Additionally, differences in the internal-external rotation moment could be explained by a clashing of the skis in mogul skiing due to the block position.

Read & Herzog (1992) found a variation between anterio-posterior knee joint forces during ski jumps between -0.12 BW and 0.51 BW and vertical forces between 1.02 BW and 1.40 BW (1.53 BW and 0.25 BW for a poor landing). These values were calculated without the consideration of muscle forces. Knee joint moments ranged from 1.25 Nm/kg to 3.75 Nm/kg (1.25 Nm/kg to 5 Nm/kg for poor landing). Study III demonstrated peaks of 5.8 Nm/kg internal-external rotation knee moments (participant 4), 3.4 Nm/kg lateral moment (participant 5) and 3.8 Nm/ kg flexion moment (participant 4), all in the ST condition with a stiff ski boot. Comparing these values to injury thresholds they appear not to be detrimental. Reid & Herzog (1992) demonstrated that sudden changes in joint moments of approximately 3 Nm/kg were found to avoid falling and may potentially cause a great risk of ligament overloading in the knee. However, internal-external rotation moments at the knee in skiing are often higher than injury threshold data presented in the literature gained from cadaver studies. The ultimate torsional moment for knee ligaments, specifically the ACL, has been determined to be 35-80 Nm using cadaver specimens (Mote, 1987). Such values are easily attained in skiing without injury. This can be explained by the protective effects of the embedding musculature. Tesch (1995) investigated elite skiers for voluntary peak moments and found knee extension moments of up to 400 Nm. Read & Herzog (1992) in their computer simulation study calculated between 100 Nm and 300 Nm for normal landings after jumps. Despite this, Read and Herzog could not conclude if the athlete would have had a large risk of injury. This compares well with the values measured in study III whereby the highest knee extensor moments were measured for participant 1 with -226 Nm in the FL condition.

Generally, in skiing, high external forces without the occurrence of tissue harm can be explained by well-directed muscle contraction absorbing a large proportion of the impact forces that would result in ligament rupture (Mote, 1987). However, it is also known that an increase in quadriceps force can significantly increase the risk of an ACL strain

(Withrow et al., 2006). As the knee ligaments are at a greater risk of injury than the tibia (Piziali et al., 1982), the knee is the weak link of the human lower extremity in skiing. Gerritson and colleagues (1996) simulated a balance disturbance in conjunction with a recovery attempt by the quadriceps muscle contraction. This led to force peaks at the ACL of 1350 N, which is within the range of failure loads. This research supports the belief that the force acting on the ACL is influenced by the intensity of contraction of the quadriceps muscles. McLean et al. (2004) assumed an anterior drawer force of 2000 N as the threshold for ACL injury. The knee moment that leads to an ACL rupture cannot be measured in vivo for ethical reasons.

Mueller and co-workers (1993) used an inverse dynamics model to calculate ACL loads and muscle forces in slalom and giant slalom racing. They assumed quasi-static conditions and estimated ACL loads of 802 N in slalom and 600 N in giant slalom. The tibio-femoral forces accounted for 5 892 N in slalom turns and 3 458 N in giant slalom turns and the quadriceps femoris forces were 5 183 N and 3 318 N, suggesting that relatively large load was absorbed by bones and muscles before reaching the ligaments. By comparison study III revealed the highest average force of 7 474 N as tibio-femoral force in the ST condition over the runs with peaks of up to 13 000 N with an average quadriceps muscle activation of 1 348 N in the ST condition over the runs. However, peak values of up to 6 700 N were reached for single participants at the instant of maximum force (participant 7). These numbers suggest that in mogul skiing more load needs to be absorbed by the muscles compared to giant slalom and slalom. Therefore, it can be assumed that the portion of ACL load is larger than 800 N as measured by Mueller (1993). Hence, 14% less quadriceps activation in the FL condition of study III in conjunction with a significant decrease of up to 30% anterio-posterior net forces at time of peak force application, suggest a decrease in ACL load with the modified ski boot.

In the current project, the increased general muscle activation in the WS and the ST condition respectively could be an indicator of muscular compensation. Spitzenpfeil (2005) described numerous factors influencing instability in alpine ski racing. Factors that have impact on the incidence of overbalancing and its possible triggers and mechanisms were searched for. Overbalancing due to the regular disturbances by the moguls, lead to a greater muscular stress, primarily caused by the considerable movement restriction in the ankle joint. The alteration of postural control when wearing ski boots due to the increased length of the supporting base by the ski boot has been described previously. Changes in

postural strategy have been found through reorganisation of muscle coordination when wearing ski boots compared to normal foot wear (Noé et al., 2009). The decrease in general muscle activation in the NS and Flex condition can be explained by an easier maintenance of the balanced position on the ski with a more natural range of movement of the boot. The maintenance of the dynamic balance has been emphasised as the most important control variable in skiing technique as it adjusts segment postures in the sagittal and frontal planes (Spitzenpfeil & Mester, 1997). Schaff (1997) determined the right regulated heel pressure in the steering phase to be a good performance indicator. In the analysis of mogul skiing turns, however, it is not the lateral movement of the legs by means of edge control as is mostly focused in alpine skiing, but the vertical movement of the legs by means of speed and balance control. In the current study III this is indicated by the range of ankle, knee and hip joint angles as opposed to minor medio-lateral changes of the path of the CoM. This averaged 24 cm and 25 cm in the FL and the ST conditions in study III and were not relevant for straight runs without turns in study II. A slight lateral movement of the legs is also required for mogul skiing, but with a small turn angle and an emphasis on regaining a neutral position in the anterio-posterior direction after the turn. A 'backseat position' in mogul skiing would potentially not lead to a smaller turn radius as described by Moessner (2008) for carved turns, but to an out of control situation with an increased risk of falling. Greater flexibility in the ankle joint favours general agility and a more advantageous position of the body's CoM at the instant of impact absorption. This reduces the knee joint loading and it causes regular control to avoid a potentially harmful backward lean position for the whole run.

Groning (1980) emphasized the importance of a well adjusted body posture in skiing with regards to the effects on femoro-patellar pressure. If the CoM remains above the base of support in a squatting movement such as in mogul skiing the lever arms are shortened through the perpendicular line through the CoM. In skiing, the inclination of the slope plays another important role concerning the lever arm relations and thus reduces or enhances the load on the knee. Figure 102,a) displays a downhill skiing position in a front lean position with short lever arms and minimal femoro-patellar pressure. This is in contrast to Figure 102,b) that shows a downhill skiing position with a more distally shifted CoM which strongly influences the lever arm of the thigh and the shank and the acting load. The values $X_{10} - X_{30}$ indicate a slope inclination of 10°, 20° and 30° (Groning, 1980).



Figure 102: Downhill ski racing position in a) a relative front lean and b) a 'backseat' position (Groning, 1980).

Thus, considerably high values are encountered when going from a steep in a flat slope section or when clearing a bump without immediately adjusting the stance which is required in mogul skiing. The values of that study were given in Kilopascal (kPa) and cannot be directly compared to the values in the current project. However, the lever arm conditions in relation to the anterior-posterior shift of the CoM in mogul skiing remain the same. Figure 102 demonstrates the effect of a distinct backwards lean which is evidently encountered in mogul skiing in conjunction with vertical and axial impacts that potentially cause this effect. Femoro-patellar compression force in study III reached, on average, 27.9 N/kg and 18.7 N/k in the ST condition at the instant of peak force and was diminished by 34 % and 31 % to 18.4 N/kg and 14.7 N/kg after using the modified shoes. This can be explained by the 5 cm anteriorly shifted position of the CoM at this point of time which is in agreement with Groning's illustration.

McConkey distinguishes active, i.e. the quadriceps-induced concept of injury, and passive, i.e. the boot-induced concept of injury. If the skier is passively forced into a backseat posture by a stiff boot he needs to actively contract the quadriceps muscles to avoid a backward fall. These events can occur in combination as a devastating injury mechanism in skiing (McConkey, 1986). Lehner (2007) and Beynnon (1998) emphasise that a decent

quadriceps contraction in conjunction with a valgus moment can lead to extensive ACL loads. This is particularly enforced at a 10° to 50° knee flexion angle. Although in study III the average knee angle at maximum force was 55° in both conditions, several single runs demonstrated knee angles between 23° and 40° when peak force was applied in the ST condition. Therefore this fell in the critical range for knee instability. A 20% to 54% greater quadriceps contraction in the ST condition in conjunction with the above mentioned increase of backward lean was encountered in study III. Additionally, a 70 % larger internal rotation torque from -0.141 Nm/kg/m to -0.463 Nm/kg/m for the right leg comply with the detrimental preconditions to injury suggested by McConkey (1986), Lehner (2007) and Beynnon (1998).

As mentioned previously, different results are subject to differences in the technical execution and the different methods used for data collection and analysis.

10.3 Comparison with other movements

This sub chapter presents examples of joint loading in other sports and compares these to the results in the current study. Walking and running have been extensively investigated with regard to shock waves transmitted from the lower extremitiesto the skull (Clarke, Cooper, Clark, & Hamill, 1985; Hamill, Derrick, & Holt, 1995; Light, McLellan, & Klenerman, 1980; Shorten & Winslow, 1992). Some impacts are necessary for the lower extremities in order to provide enough loading for bone remodelling. However, it is difficult to ascertain at which stage this positive effect turns into an overloading of the joints or bones of the hip knee and spine (Simon, Radin, Paul, & Rose, 1972). Repetitive impacts are part of the normal mogul skiing technique, however, these loads differ from running or similar sports. Yamamoto (2003) demonstrated that fast dynamic loading conditions result in higher loads to the ACL than more static loading conditions. This might hold true for mogul skiing.

Inline skating is recommended as a useful exercise modality for reduced impact shock during aerobic training (Jerosch, Heidjahn, & Thorwesten, 1998). Mahar (1997) demonstrated reduced vertical movements in inline skating. In this sport, horizontal velocity prevails over vertical velocity at foot contact so there is a smoother transition from swing to stance leading to a lower impact force for the body to attenuate. Kroell et al. (2003) revealed similarities and differences in movement patterns of inline skating compared to slalom skiing. With regard to impact forces the differences may more prevail

for mogul skiing which means that inline skating could be a useful training tool for skiiing. It might be an appropriate discipline for endurance and coordination. However, further work is required in the kinematics, kinetics and neuromuscular characteristics in order to compare joint loading with other sports and to fully appreciate its potential (Mahar et al., 1997).

A single leg rapid deceleration movement following a 1.5 m hop results in a 1000 N ACL strain measured with a surgically implanted strain gauge (Cerulli, Benoit, Lamontagne, Caraffa, & Liti, 2003). The validated data from a single individual suggests that the increased ligament strain, during the rapid deceleration task, causes ligament elongation. It is unknown and difficult to measure if such loads can surpass the fibrous structure's elastic capacity thereby causing permanent damage to the ligament. This is due to the multibundle structure of the ligament and because it is attached in the joint. The fact that the ligament strain increases notably prior to impact indicates a preparation for muscle activation to stabilise the joint. Having the feet held in a braced position distinguishes freestyle skiing from most other sports. The single leg deceleration jump is a similar movement to mogul skiing except mogul skiing comprises an inclined slope and usually includes both legs. Higher speeds and less friction further distinguishes skiing from the the single leg jump and the attenuating movement is more constrained due to the stiff ski boot. However, with measured peaks up to 129 N/kg for aneroposterior forces at the tibia and GRF of up to 7.73 N/kg for one leg, the ACL loads are presumably higher in mogul skiing. These results have to be interpreted with caution as Cerulli's in vivo measurement technique is assumed to be more precise than the modelling approach in the current study.

Another movement that has been investigated to estimate ACL tension is drop landings. Previously, several laboratory based investigations of jump landings were conducted. Vertical forces of 9.1 N/BW were measured from a height of 1.28 m (McNitt-Gray, 1993). Zhang et al. (2000) gained similar results from a slightly lower height, although different forces between 4.4 N/BW and 3.2 N/BW were measured for lower drop jumps off 0.6 m and 0.72 m boxes (McNitt-Gray, 1993; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004; Zhang et al., 2000). Vertical GRF between 2.1 and 2.56 N/BW were measured for the lowest drop height of 0.3 m, as demonstrated in Table 21 (McNair & Prapavessis, 1999; McNitt-Gray, 1993; Zhang et al., 2000). In study III GRF of 2.4 BW were measured, on average, for both legs at the instant of peak force, but up to 4.8 BW for a single participant (no. 4). The compulsory jumps in mogul skiing are approximately six meters in height Ut List of research project topics and materials

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(Babic et al., 2006), thus suggesting higher values than indicated for these studies testing lower heights. However, this has not been investigated in this project. Mogul skiing turns do not consist of jumps, because the skier tries to retain snow contact. But the skier still experiences repetitive impacts, each of which get absorbed by the legs as the body's natural damping system. According to Kernozek (2008), the ACL tension gets reduced by the posterior pull of the hamstrings which is most effective later in landing movements with larger knee flexion angles. The current study cannot provide clear evidence for efficient muscular activation with respect to ligament protection, but a trend to protective activation patterns is illustrated. In Figure 103 a representative example of knee angles plotted against hamstring muscle activation shows a hamstring activation peak before maximum knee angle in the FL condition and at maximum knee angle in the ST condition.



Figure 103: Left knee angle plotted against hamstring muscle activation for participant 1 in a) an FL run, b) an ST run (FL_RHam=right hamstrings in FL condition, FL_RKNFlexAng=right knee flexion angle in FL condition).

The GRF values of the current studies compare well with McNair et al. (1999), McNitt (1993) and Zhang et al. (2000) (Table 21). Based on these comparisons it appears a drop height of between 0.3 m and 0.6 m would be required to generate the GRFs experienced in mogul skiing. However, it should be considered that forces up to 1.5 BW can be absorbed by the front shaft of the ski boot which can vary depending on the position on the ski (Kersting & Kurpiers, 2010). Moreover, all participants performed relatively moderate technique execution as an inclination of 25° did not require extreme positions at high speeds. Therefore the focus was on the boot intervention under controlled conditions rather than gaining realistic competition forces. Thus, a steeper slope of 35° inclination with speeds closer to competition runs is likely to increase GRF.

With 19° minimum knee flexion angle in study II and minimum knee flexion angles of approximately 23° in study III during main impact the current results are within the indicated range of potentially critical knee angles causing joint vulnerability. ACL failure values on cadavers vary within the literature. A younger specimen, investigated by Wu (1991) showed more persistent ACL's than Hollis (1988). Also, cadaver studies are very generalising as not many cadavers were used for such studies. It remains unknown if an adaptation by skiers would have an effect for ligaments. The measured values of the current study did not reach the injury tolerance levels as indicated in the literature. However, it can be assumed that the lower indication of 1 200 N can be attained in mogul skiing following a loss of control with greater GRF and joint moments.

Table 21 displays various parameters related to skiing and other sports concerning measured forces and injury thresholds. GRF on a single leg in mogul skiing are in agreement with those measured for running (Arampatzis, Brüggemann, & Metzler, 1999). However, kinematics of running differ from mogul skiing in that an alternating movement cycle with exploitation of joint angles occur to a great extent. The running movement was a controlled and straight and thus did not include any disruptions that could put the ACL at risk. In contrast, lateral moments due to change of direction in running indicate a potential risk for the ACL (Besier, Lloyd, Ackland, & Cochrane, 2001). Varus valgus moments of more than 200 Nm in cutting movements without any anticipatory preparation compare well with those measured study III.

| PARAMETER | CONDITION | VALUE | LITERATURE |
|--------------------------|-----------------------------|-----------------------|---------------------|
| ACL failures measured on | | 1200 peak | Hollis, 1988 |
| cadavers [N] | | 2160 peak | Wu, 1991 |
| | | 35-80 Nm peak | Piziali, 1982 |
| | | (ultimate torsional | |
| | | moment) | |
| Peak GRF skiing/ | Snowboard Jumps | 11 | McAlpine, 2009 |
| snowboarding on SL | Carved skiing | | |
| (N/BW) | Giant Slalom | 3.6 | Klous, 2007 |
| | Mogul skiing | 1631 N* | Raschner, 1999 |
| | | 2.4 (ST) | Current study |
| Peak GRF non skiing | Walking | 1.16 | Schwameder, 2004 |
| (N/BW) | Running | 2.4 - 3.4 | Arampatzis, 1999 |
| | Drop landing (0.33 | | Madigan, 2003 |
| | m) | 3.69 | |
| | (1.28 m) | 9.1 | |
| | Push off back somersault | 2.78 | Mathiyakom, 2006 |
| ACL (PCL) loads skiing | Slalom | 802 (823) | Mueller, 1993 |
| (N) | Giant Slalom | 600 | |
| | Ski jump landing | 1350 | Gerritson, 1996 |
| ACL loads in non-skiing | Drop landing | 94 | Kernozek, 2008 |
| (N) | | | |
| VV loads skiing (Nm) | Parallel turns | 70-149 | Quinn, 1992 |
| | Skidded turns | 97 | Klous, 2007 |
| | Carved turns | 431 (peak) | |
| | Mogul skiing | 211 | Current study III |
| VV loads non-skiing (Nm) | jump landing | 106 | Withrow, 2006 |
| | running/ cutting | 125-210 | Besier, 2001 |
| Critical range of knee | | 20°-40° (instable for | Girgis, 1975 |
| flexion angle | | VV) | Besier, 2001 |
| | | 0°-20° (largest ACL | Markolf, 1993, 1995 |
| | | 10aus) 10°-50° | Beympon 1992 1998 |
| | | 10 50 | Beymion, 1772, 1770 |

Table 21: Knee loads found in the literature with regard to ACL failure or high values encountered in skiing or other sports (PCL=Posterior cruciate ligament, VV=varus valgus). SL=Single Leg,

*no BW was indicated

The hip compression forces calculated by the model in the current studies are very high. As mentioned in the discussion of study II (chapter 8.5) several factors contribute to these high values such as the GRF and the distance of the hip to the base of support, specifically the lever arm to the point of force application. Furthermore, the extensive hip angle and the co-contraction of several joint wrapping muscles such as the glutei, iliopsoas and hamstrings can lead to values of more than 20,000 N (approximately 25 times BW). An eccentric muscle activation is commonly encountered in mogul skiing and is usually higher than a concentric activation further raising the compression forces (Berg & Eiken, 1999; Kellis & Baltzopoulos, 1998). In the previously discussed project, a distinct involvement of the abdominal muscles was reported, which supports the explanation of such values (Machens, 2006). The abdominal muscles were not selected for illustration,

but were included in the Anybody 'Mogul Man' model. According to Correa et al. (2010), muscles are the major contributors to hip contact forces including muscles that do not span the hip such as the vasti, the soleus and the gastrocnemius muscles. Cholewicki et al. (1991) found more than 17 000 N as average compressive loads and more than 1 000 Nm for hip moments during weight lifting. Another study found hip joint compression forces of nearly 900 % to up to 7 000 N in a normal walking disrupted by stumbling (Bergmann, Graichen, & Rohlmann, 1993). On the search of realistic net joint moments on the lower extremity in skiing, Friedl (2007) offers some maximal strength values. Experimental data revealed net joint moments as high as 500 Nm for the hip (300 Nm for the knee and 154 Nm for the ankle) is in agreement with the current results.

10.4 Implications for injury prevention strategies

Implications for injury prevention strategies derived from the current data incorporate the scope of equipment modifications and the improvement of technique modification. The current project comprised both of these areas since the use of the new boot requires a distinct change in technique.

Schaff and colleagues (1993) refer to the "big bump flat landing' phenomenon and it is relevant and frequently encountered in freestyle skiing. The research group investigated a modified ski boot that opened the rear spoiler for the shank in a backward fall situation at a certain pre-determined force. Benoit et al. (2005) found a reduction in ACL load when the cuff released, but a second increase immediately after the release back to the prerelease condition. It was concluded that an injury preventing effect was difficult to predict from these findings. Schaff further distinguished three different stiffness classifications and found that loads at ligaments in a soft setting are lower. A softer boot with less resistance at the rear spoiler significantly reduced the peak forces acting on the shank when falling backwards. The deceleration of the tibia occurred without stopping, whereas a stiff ski boot showed higher maximum force values and a faster increase at the back spoiler. An injury situation on the slope is likely to comprise a combination of loads as originated from a backward lean or fall with rotation of the tibia and the trial to recover. Such a situation can lead to short peaks that have the potential to damage the strongly tensioned ligaments, as it is the case in the 'big bump flat landing' or BIAD injury mechanism (McConkey, 1986; Schaff & Hauser, 1993). These high force peaks acting on the preloaded tendons and ligaments are often not tolerated by anatomical structures and the muscles are not able to react fast enough to brace the leg. If an impact can be anticipated by the skier so as to brace the leg, the quadriceps-induced ACL rupture mechanism poses risk in such situations (Schaff & Hauser, 1993). The current study used a similar principle as Schaff with regards to softer ski boots and its effect on reducing peak forces that were transmitted by the ski boots and acting on the legs. However, Schaff modified the boot at the spoiler expecting a backward lean position due to the boot restrictions in the anterior direction. This is contrary to the current studies that applied the greater boot flexibility to the anterior part of the boot which influences the ankle joint flexibility towards a more distinct forward lean. This should lead to the maintenance of a neutral position on the ski so that the harmful backward lean can be avoided. Thus, the current project follows a concept of injury prevention by means of avoiding potentially dangerous body postures. In contrast Schaff & Hauser (1993) try to limit the damage during the ongoing event. According to Schaff, a back spoiler should serve two requirements in extreme situations 1) support to regain the normal skiing position (recovery) and 2) not harm the lower leg by applying too much initial forces to the knee (Schaff & Hauser, 1993). The current approach showed that expert mogul skiers are able to maintain a more forward lean position at peak force when using the modified ski boot. Therefore the risk of getting slingshot (unintentional loss of snow contact) in a 'backseat' position is potentially reduced. According to several participants' questionnaire statements in study III, the back spoiler can be used to push forward and adjust the middle stance. This is in agreement with a 12% to 22% reduced backward acting moment measured at the boot sole from -56.8 Nm and -56.0 Nm in the FL condition of study III to -64.0 Nm and -71.0 Nm in the ST condition.

Schaff used a stiff, a medium and a soft boot representing the degree of flexibility of the rear spoilers. The participants gave poor feedback for the soft boot and evaluated it too unstable whereas the medium boot was rated more highly which is in accordance with Machens' (2006) perception results. Therefore the conscious decision was made in study III to not change the boot properties drastically (as in study II) so to maintain the participants' confidence and acceptance.

A more recent study, showed a distinct dorsally shifted CoM during skiing with a stiff ski boot (Bürkner & Simmen, 2008) which is in accordance with the results of study III at peak force. Bürkner & Simmen (2008) observed that ski boot forces can be transmitted to the leg more gradually with a more flexible boot which is not possible with a stiff ski boot.

Abrupt movements that occur in the passive injury concept (e.g. BIAD) normally lead to a sudden tension that can theoretically lead to lower leg fractures at the higher end of the ski boot shaft. This supports the idea of using a more flexible ski boot as this can lead to ACL ruptures.

Spitzenpfeil and colleagues investigated the neurophysiological aspects such as sensation improvements for precise movement regulation e.g. at the ankle joint receptor (Spitzenpfeil, Babiel, Rieder, Hartmann, & Mester, 1996). According to the authors small displacements in this joint cause remarkable changes of posture and lead to an increased movement regulation. This supports the idea that a greater ankle joint flexibility aids control of the position above the base of support and is in agreement with the current results reflected by the greater ankle and knee joint flexion in conjunction with more forward lean at peak force. The anterio-posterior adjustments of the body posture with stiff boots may not be achieved by less fit skiers due to muscle fatigue. Raschner (2001; 2001) suggested a regular training towards increased proprioceptive balance and coordinative training for better performance. A flexible ski boot can improve sensation in general because proprioceptive procedures are likely to be activated due to an increased agility.

The current concept is potentially useful and beneficial for expert skiers like the participants in study III. However, this alteration may also be advisable for beginners. Hall (1991) compares the assumptions that the current project is based on that stiff ski boots lead to an upright or backward lean position while skiing. This is potentially dangerous with regard to loss of control and thus overloading of ligamentous structures at the knee. Schaff found a 20% lower forward lean capability in beginners compared to expert skiers with stiff boots that can impede learning. This demonstrates that greater ankle flexibility is also important at a lower skill level to avoid harmful body postures during skiing (Schaff & Hauser, 1989, 1990a, 1990b).

Schwameder et al. (1997) stated that simulation jumps are not suitable for technique training in ski jumping and even have a negative influence on jump technique. According to the authors, a major goal was to improve training and determine the foundation for individualisation. In order to provide off-snow training to the ski mechanics and biomechanics of the skiers the jump technique needs to be examined on-snow (Campbell, 2002). Such a training improvement, e.g. for the so-called 'dryland programs' in mogul skiing, could be developed from the current data base. A useful drill is the 'grasshopper',

i.e. hopping down an inclined grassy hill with landing holes of approximately 0.5 m depth that are spaced left to right as a mogul field (Figure 104). The subject should jump and absorb the speed quickly in the next hole holding ski poles and keeping the mid core as still as possible. Executing this drill with the modified ski boots would implement the necessary familiarisation for training in a safe and controlled environment. Since the stance phase is the major factor in balancing, it should be trained and prepared for as similar as possible to the real skiing situation in the off-snow season. This drill may rather be appropriate for expert and competition freestyle skiers, but beginners and advanced beginners can use these boots for other drills such as wobble board exercises or rolling with one leg on a skateboard, performing moderate little jumps on a mini trampoline or simple squats. These drills have been recommended before (Raschner, Schiefermueller, Zallinger, Hofer et al., 2001) and can provide strength, improve balance, coordination and sensation incorporating the modified ski boot.



Figure 104: World Champ Jonny Moseley's dryland training (hopping downhill from hole to hole on a man-made track to simulate mogul skiing)

Nyberg (2006) emphasised the importance of preventative training in specific disciplines since it is difficult to recover to preoperative functional level after ACL reconstruction. The findings of the current study and suggestions with regard to prevention strategies in the form of training interventions should encourage and inspire athletes and coaches to consider training and equipment changes.

10.5 Computer modelling

The musculoskeletal model used in the current project was based on an existing full body gait model that utilised the TLEM for lower body movement reconstruction. The TLEM was developed by Klein Horsman (2007) and has a valuable advantage that distinguishes it from other models. According to the developers the major advantage of this model is that the parameters are based on only one cadaver which makes it more consistent as opposed to other models that are often merging model parameters measured from different subjects (Anderson & Pandy, 2001; Delp et al., 1990; Higginson et al., 2006). Some of the named researchers attempted to enhance the model quality by adding extra information, however most of these parameters were based on assumptions rather than anatomical measurements which increases the risk of inconsistency (Klein Horsman, 2007). An inaccurate moment arm, for instance, elicits inaccurate muscle force boundaries in muscle force optimisation strategies. Maximal isometric muscle forces, based on the data set of Delp (1990), were compared to the TLEM and revealed differences in the contributions of the muscles.

An innovative approach was used with the TLEM and was included in the Anybody modelling software[™]. By including a forward muscle model into an inverse optimisation method, muscle dynamics were included in the force boundaries. By contrast to other models, such as Heller (2001), this approach enforces realistic transitions in muscle force. Furthermore this method is faster than conventional forward simulations. Commonly, model parameters are proportionally scaled with the same ratios as the subject segment lengths. However, it is challenging to scale internal parameters such as sarcomere or tendon slack lengths since they are not immediately accessable. These unverifiable model parameters are based on assumptions and scaling rules, the accuracy of which remain unknown (T. S. Buchanan, Lloyd, Manal, & Besier, 2005b). The TLEM was more extensively validated than other models. Apart from minor deficiencies for 'unskilled movements', i.e. not normal ranges of movement in conjunction with unconventional angular velocities, it has been found to be more accurate than several other models. Cycling is one 'skilled' movement that it has been validated for, which is assumed to be similar to mogul skiing with respect to knee range of movement and angular velocity when skiing on a moderate slope (Nordeen-Snyder, 1977). Without any merging and tuning of anatomical datasets, the TLEM estimated muscle forces are in agreement with EMG and in vivo measured joint compression forces, which enhances the reliability of the predictions of the current model (Klein Horsman, 2007).

Friedl (2007) used two different 2D models for comparison in a wave slope in the sagittal plane (chapter 10, 'Comparison with mogul skiing literature'). This project investigated very similar parameters in a similar test setup as study II. One of the models was a rigid body model and is commonly used in the area of snowsports and the other was a wobble mass model taking soft tissue movement into account. Evenly distributed forces and moments were assumed for both sides of the body. This assumption, however, was disproved by the results of the current project since in study II partly considerable differences between both body sides were found in forces, moments and joint angles. The goal of Friedl's study was to find an appropriate instrumentation to aid data processing for parameters that are not directly measurable in the field such as constraint forces or net muscle moments. A drawback of his approach was that a 2 D model was used. Although no turns were involved in the data collection it remains questionable if a 2D model provides sufficient information as a 2D model is an oversimplification of the true dynamics. Despite this it should be mentioned that for a potential mono-axial movement such as the wave slope runs the differences in specifications between different models can presumably lead to a similar risk of imprecision. The application of the wobble mass model was evaluated in more depth compared to a rigid body model as used in the current project. The wobble mass movement was attenuating the oscillations of the bones and elicited a reduction of the net joint moments. Hatze (1977) estimated the measurement error of the rigidity approximation assumption to be approximately 6%. Gruber (1987) suggested different results for dynamics if the egomotion of the soft tissue is considered in the model for movements with high accelerations. A more recent study, demonstrated a reduction of the resultant GRF and moments in drop landings of nearly 50% using a wobble mass model compared to a rigid body model (Pain & Challis, 2006). However, comparing the current results to other studies the 'Mogul Man' was beneficial to show that joint loading depends on joint angles and body postures during mogul skiing.

10.6 Limitations of the current project

10.6.1 Kinematic and kinetic measurements

There are a number of general limitations in the current thesis, which need to be considered when interpreting the results. The precision of the kinetic measurements (= force platform) was expected to be given based on the validation presented by Kiefmann

et al.. However, due to the assembly of the force sensors the top and the bottom plate of the force plate had some movement in relation to each other, which was negligible according to the participants' perception as stated following the period of familiarisation. However, the clearance of the top plate in relation to the bottom plate can theoretically produce an alteration of the lever arm to the knee. Additionally, forces and moments are assumed to be more precise when skiing straight with the CoP within the triangle assembly of sensors as explained in chapter 7.1.1 (Kiefmann, 2006). Comparing the current results with other human movements is difficult as the investigated motion differs from other investigated movements with regard to its performance execution and thus GRF combined with the given lever arms and shear forces. Additionally, measurement devices used in different skiing studies were attached to different interfaces, put additional weight to the skier-boot-binding-ski-system and had different impacts on the participants' perception and thus their acceptance. Hence, these aspects should be considered.

The field testing environment could have had negative influence on the precision of the kinematic data compared to the precision tests conducted in a controlled laboratory based environment. Poor lighting for the indoor tests (study I) and changing lighting conditions for the outdoor tests (study II and III) made a manual digitisation method over an automatic digitisation approach necessary as clouds and fog required image brightness and contrast to be continuously readjusted. Additionally, the participants needed to wear a race suit due to the cold temperatures and safety reasons and therefore marker shifts might have happened (chapter 6.3). However, the sensitivity analysis (chapter 7.3.7) revealed the effect of marker misplacement with regard to anatomical structures negligible. The initial individual fit of the markers was ensured by an investigator prior to each test run so that the risk of imprecision was minimised. Fixation of the cameras was a challenge in an alpine environment under windy weather conditions. The investigators, however, evaluated this source of error to be minimal as ice buckets and ropes held the tripods stable and no unintentional camera movement has been noticed within one testing day. If a possible risk of camera movement was observed the calibration of the system was repeated.

The major setback was experienced in study II where adverse weather conditions, thus a considerably reduced training period and the loss of kinetic data due to computer breakdowns due to cold or altitude happened. For study III some of the drawbacks from study II were compensated for.

V=V List of research project topics and materials

10.6.2 Modelling limitations

There are several limitations associated with the utilisation of computer models in order to predict soft tissue loading in the current application. In real life body segments are not rigid and the soft tissue behaviour is dependent on several aspects such as contraction of the musculature. Several studies have shown that rigid body models have limitations compared to wobble mass models and carry the risk for imprecisions as discussed in the previous chapter.

The modelling of the ankle and knee joints as fixed axis revolutes does most likely not match reality. Several studies identified changing axis location and orientation throughout the range of motion at the ankle joint (Arndt, Westblad, Winson, Hashimoto, & Lundberg, 2004; Hamel, Sharkey, Buczek, & Michelsen, 2004; Leardini, O'Connor, Catani, & Giannini, 1999a, 1999b; Lundberg, 1989). However, for the majority of applications in biomechanical research it is generally tolerated to think of the ankle as a hinge joint with the axis of rotation through the the malleoli of the tibia and fibula (R. Bahr, Pena, Shine, Lew, & Engebretsen, 1998; Leardini et al., 1999b; Leardini, Stagni, & O'Connor, 2001; Lundberg, 1989; Wu et al., 2002).

The human knee joint is comprised of the femur, tibia and the patella. The forces can be defined by six interactive forces and six active torques (Komistek, Stiehl, Dennis, Paxson, & Soutas-Little, 1997). The knee joint experiences motion patterns unlike those of any other joint in the human body, i.e. the patella rotates and translates with respect to the tibia while remaining in contact with the femur (Komistek, Dennis, Mabe, & Walker, 2000). It is therefore difficult to model the knee as is therefore considered a hinge joint (Besier, Lloyd, Cochrane, & Ackland, 2001; Dendorfer & Toerholm, 2008; Kernozek & Ragan, 2008; Komistek, Kane, Mahfouz, Ochoa, & Dennis, 2005). If a hinge joint is assumed and the patella pulley is modelled from rigid elements it can create high forces. Additionally, for the current project a simple muscle model was used simplifying the muscle recruitment and activation patterns. It has a tendancy to overestimate the muscle activation leading to the calculation of high muscle force values (chapter 0). Thus, the results should be interpreted with caution, however, comparability is given due to the employment of the same model in all conditions.

The argument that a model based on only one cadaver is more precise than a model which is an average of a number of cadavers is arguable. The internal validity in such a model is given whereas there is a risk of lacking external validity. Although interindividual differences between thigh and shank lengths were taken into account by the model different tested subjects have different muscle and joint geometries that could not be considered by the model.

It is difficult to directly transfer the technical expertise from the area of robotics to musculoskeletal computer simulations of human movements. This is due to the fact that electronic control units are notably simpler than the human biological system. The sensory interaction abilities of the human body such as visual, vestibular and somatosensory systems as well and the existence of tension receptors of the musculature are difficult to simulate. Moreover, biological systems are often over-determinate. In the knee there are bony structures, four ligaments (sub-divided in fiber bundles), two menisci, joint capsules and ten muscles transmitting the forces between tibia and femur (Senner, 2002). Solving this redundancy problem requires additional mathematical equations. Generally the accuracy of a model is highly related to the accuracy of the motion capture data. Results should be interpreted with care due to the mentioned limitations.

Chapter 11: General Conclusion

This chapter will summarise the most important findings and the possible implications of this project with regards to equipment and technique development and includes the implications for injury prevention strategies. Finally the concluding remarks will point out to prospective future directions in the area of snow sport research.

11.1 Contribution of the current project

A systematic quantitative biomechanical analysis of mogul skiing turns was conducted and recommendations on injury prevention based on the findings were given. The body posture investigated was the crouched position and changes in joint angles at the ankle, knee and hip joint. These variations are substantial in determining the body positioning on the ski with respect to anteroposterior, medio-lateral and proximal-distal adjustments. As conventional ski boots influence the maintenance of this posture above the base of support, it is characteristic for this investigated posture that the angle of the shank in relation to the 'normal' direction is smaller than the angle between the thigh and the 'normal' direction (perpendicular to the ski). This results in a backward lean of the CoM relative to the base of support. More anteriorly flexible ski boots are able to change this. The flexed position is constitutive for general movement patterns in skiing. All postures are variations around a shift of the CoM in all three directions. Although applicability of a more flexible ski boot in carved turns could be criticised due to a (subjectively) perceived lack of flexion resistance, the proposed ski boot feature has the potential to be applied to freestyle disciplines that involve great joint angles and landings.

Mogul skiing performance has not been comprehensively investigated previously. To date, studies used either, only a straight line for performance as in the current study II (Friedl, 2007; Machens, 2006) not accounting for turns, or insufficient measurement equipment for the calculation of 3D joint loading (Schaff & Olbert, 1996). Comparing the current results to other skiing techniques such as carving or slalom is difficult as the force distribution, front and side lean and the relation between peak forces and joint angles differ considerably. The most important results are listed below.

Summary of main findings:

Following the ski boot intervention the current project showed

- A change in the body position
 - o A greater range of movement, particularly at the ankle joint
 - o Forward shift of the CoM at force maximum
- Reduced GRF
- A change in the net forces and moments in the ankle and knee joint
 - Reduced anteroposterior tibia force indicating the load on the passive structures of the knee, i.e. the ACL
 - Reduced femoro-patellar compression force at maximum force
 - o Reduced ankle extension moment
 - o Reduced knee flexion moment
- Reduced muscle activation in the lower extremities for the
 - o soleus
 - o gastrocnemius
 - o vasti
 - o hamstrings
 - o rectus femoris
- The general acceptance of the modified ski boot by freestyle skiers
- A positive evaluation of the modelling approach with regard to the calculation of net joint loading accounting for muscle force contribution

The general willingness of skiers to engage in new equipment and thus relearning of techniques seems to be limited since the introduction of the carving ski in the mid 1990's (chapter 1.2). On the other hand this bias could also be attributed to the promotion and innovations of equipment by the industry. The industry and manufacturers became more cautious with unconventional innovations in the course of the recent recession. Hence the bias of the consumer as well as the scepticism or reluctance of the manufacturers dictates

such developments. This thesis is supposed to serve as motivation to disassociate from traditional structures and progress the understanding of skiing equipment and technique. The results presented form a data base which may be used for further investigations in the widely unexplored area of freestyle skiing. This could cover the perspective of injury prevention strategies and performance optimisation. The following section will delineate potential future directions for skiing biomechanics.

11.2 Future directions

From the current data net moments and general joint loading could be derived using the Anybody computer model. Although a general decrease of tissue loading could be assumed, due to reductions in the net forces, no specific distribution of load within the passive structures could be concluded. The loads on specific tendons and ligaments, such as the ACL, would be of particular interest as these compose of the majority of ski injuries (Hunter, 1999). Friedl (2007) referred to a more specific knee model of Lehner (2007) that is potentially capable of modelling the elastic sub structures of the knee.

The AnyBody Technology research group is currently working on an individual specific knee model. In particular it is aimed at including the influence of global muscle forces and their influence on the segment positions. Further a more advanced approach to the calculation of joint loading is intended with surface to surface constraints. This will be realised in conjunction with new methods of optimising the scaling (segment and joint properties) for a more specific model.

Spitzenpfeil (2005) investigated injury prevention in alpine skiing. To gain more valuable insights the author advised that researchers from different fields, such as physiology, psychology or biomechanics, create an interdisciplinary approach into the analysis of skiing. In addition, this can be extended to 'within discipline' analysis such as downhill racing, recreational alpine skiing and freestyle skiing including many unexplored movement patterns.

Buerkner (2008) suggested a standardized declaration of ski boot flexibility is required for comparison between boots. The companies Salomon and Nordica report the force (in Newtons) needed to bend the shaft about one degree forward as the value for stiffness whereas other companies report different or no values.

The current project required a lot of planning and the implementation and processing of the data was difficult and time consuming for all three studies. Approximately 1 300 000 points were digitized and took approximately six months to analyse. Therefore, it would be desirable to establish a technology that would speed up this process, such as a markerless fusion motion system (gyroscopic sensors) as presented by Brodie (2008). The force plate used for the current project required a design improvement following breakages in study II. Following its repair and revision for study III it was fully functional for the intended application. Despite this, it needs to be optimized with regard to its capability for greater impacts, such as jumps, since this may be the future of freestyle skiing research. The prospective area of ski boot research could be extended as areas of freestyle skiing have not been investigated. Therefore, current study has been extended and a 'jump study' was conducted based on the findings to investigate the new boot on applicability in other freestyle skiing disciplines. Safety bindings must correspond with ski boot innovations and future research should consider these aspects in order to aid the reduction of the prevailing high incidence of knee injuries in skiing. Therefore the binding settings must match with ski boot properties.

In conclusion, this work covers an extensive developmental process leading to a methodology which leads to a final study allowing to test specific hypothesis and with that adding to the understanding of freestyle skiing mechanics. It is, however, anticipated that it may stir the interest in this area and with that induces a further extension of our research activity.

Epilogue

"It is confidence in our bodies, minds and spirits that allows us to keep looking for new adventures, new directions to grow in, and new lessons to learn - which is what life is all about" (Unknown, 2004).

In closing this work, I would like to write some important notes about the development and the people that were involved.

After suffering an ACL rupture in 1999, my concern with regards to the biomechanical parameters in freestyle skiing grew. This interest became particularly focussed on the loading of the knee joints and the spine. When I met my first supervisor, Dr. Uwe Kersting, who was at that time supervising a snowboarding project in New Zealand, I saw an opportunity to accomplish several things at the same time. This was specifically the achievement of the doctoral degree to be able to become a University lecturer in Physical Education. Furthermore, I wanted to write a thesis in English, get to know the lovely country of New Zealand, and last but not least, to investigate the burning research questions about joint loading in freestyle skiing.

After initially experiencing some major setbacks in New Zealand, the project could finally commence in early 2007. The research was very international as the first study was conducted in Auckland, New Zealand, the second study in Zermatt, Switzerland and the third in Garmisch, Germany. In hindsight, conducting these three studies was very exhausting, time and money consuming and sometimes required a good portion of willpower beyond what I thought I was capable of. I learned a lot within the last three and a half years about the topic, about me and about other people that were involved by some means or another along the way. In the spirit of the above quotation I'm looking forward to the future. I am honestly grateful that I was privileged to be able to do what I did with the support that I received.

Nico




Department of Sport and Exercise Science Nico Kurpiers Biomechanics Laboratory, Building 750 Phone 0064-(0)9-373 7599 extn. 82561

Participant Information Sheet

Project title: Dynamics of Freestyle Skiing – Equipment Development and Implications for Injury Prevention Strategies

| Principal Investigator: | Nico Kurpiers (PhD Candidate) |
|-------------------------|---|
| | Department of Sport and Exercise Science |
| | Biomechanics Lab, Building 750, Tamaki Campus |
| | University of Auckland |
| | Phone 0064-(0)9-373 7599 extn. 82561 |
| | n.kurpiers@auckland.ac.nz |

You are invited to participate in the above named research project, which is being conducted by Nico Kurpiers (PhD Student) and Dr. Uwe Kersting (Co-supervisor). The general aim of the proposed project is to identify the body movements and impact forces involved in mogul skiing technique. The results of this study will be used to develop a unique data base which will be used for injury prevention strategies and equipment design improvements.

Participant Eligibility

All persons who participate in mogul skiing competitions on a regular basis (or did so) and have done so far at least 1 season at an advanced level are possible candidates for participation in this study. Apart from that there are a few considerations to elect a homogenous group of participants. Participants should not show

- 1. any kind of acute or not fully healed injury
- 2. pain during or following training
- 3. a fracture of the lower extremity within the last two years
- 4. a severe ankle or knee trauma within the last two years
- 5. leg length difference of more than 1.5 cm
- 6. Severe abnormalities of leg anatomy

Some of these points can be answered easily. If you're interested but don't feel sure if you fulfil the criteria please check with us.

Procedures

Your agreement to participate in all procedures used in this project will be obtained in writing on a Consent Form. The project will be conducted in Zermatt ski field, Switzerland. Prior to data collection, your body condition will be checked for any particular features which might exclude you from participation. The actual testing requires an intermediate amount of preparation, since a variety of parameters have to be obtained.

3D Video recordings will be made to analyse movement dynamics. The system used in testing involves a set of reflective markers which are fixed to body landmarks using a mild adhesive tape. Your full body motion will be recorded by the camera system. The relevant sequences will be transferred to a digitising computer system and analysed off-line.

You will have to perform three mogul runs in a controlled riding situation with your own ski boots. Ground reaction forces will be measured using the purpose-built measurement device, which is a mobile force plate to be attached at the interface between ski boot and binding (figure 1). The ski boot will be fixed on this force plate with a lever and the force plate will be clicked onto the binding. Thus there is no additional risk for the skier due to the safety release.

After this testing session, all participants will receive a pair of modified ski boots to train with for one hour per day for the next three days in order to get accustomed to the new equipment. This modified ski boot will induce a significantly greater forward lean and thus a more advantageous position of the body's centre of mass. On the third day of familiarization, the test session will comprise of another series of three runs down the same mogul course with the modified equipment.

A standard binding system will be used with two inbuilt force measuring devices which will enable impact forces and joint dynamics during movement to be assessed. Depending on the phase of study in which you are tested we may ask you to use your own boots or boots provided by us. Bindings will be adjusted according to ski servicing guidelines or your personal preferences to minimize injury risk.

Pressure sensor insoles will be inserted into the ski boot to allow the assessment of foot motion within the boot. The procedures used will not have any damaging effects upon your personal property.

The risks involved with the experimental tasks are minimal. However staff trained in first aid will be at close hand in case of an emergency.

We would also need to collect some information about your training and sporting history. This will be done in form of a confidential questionnaire where we would ask you to provide a rough training history.

Due to the rather extensive preparation procedure the whole experiment will take about one and a half hours (1.5 hr) in total. No invasive techniques will be applied.



Data collected in this study will be used in studies planned in the near future. Data will be stored on password protected computers. Written information will be stored in a locked filing cabinet in the Department of Sport and Exercise Science. Access will only be granted to the Principal Investigator and Supervisor. Data will be stored for 6 years and will be destroyed after this period.

Further details will be provided by the principal researcher.

Your Rights

- Your participation is entirely voluntary. If you choose not to take part you will still receive the usual treatment/care.
- You may withdraw from the project at any time without providing a reason.
- You may have your data withdrawn from the study within three months of data collection.
- You may obtain results regarding the outcome of the project from the experimenters upon completion of the study.
- Your identity will be kept strictly confidential, and no identification of you or your data will be made at any time during collection of the data or in subsequent publication of the research findings.
- Discomfort and incapacity has not been reported from any of the procedures that will be used in this project, however, if the procedures cause you concern, you may withdraw from the project.

If you would like to participate in this research project or if you have any questions about the project, please contact Nico Kurpiers or Dr. Uwe Kersting at the address/phone number provided:

Nico Kurpiers (PhD Candidate) Department of Sport and Exercise Science Biomechanics Laboratory, Building 750, The University of Auckland, Tamaki Campus Phone office +64-(0)9 7599 82561, <u>n.kurpiers@auckland.ac.nz</u>

Dr. Uwe Kersting (Co-supervisor) Associate Professor in Biomechanics Center for Sensory-Motor Interaction Aalborg University, Denmark <u>uwek@hst.aau.dk</u> Phone office: +45 9940 8094 The Head of Department is:

Dr. Heather Smith Room 319, Building 734, University of Auckland Tamaki Campus Phone 3737599 extn 84681

If you have any queries or concerns about your rights as a participant in this study you may wish to contact:

The Chair University of Auckland Human Participants' Ethics Committee Private Bag 92019 Auckland Telephone 373 7599 extn 87830

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE on 9 May 2007 for a period of 3 years, from 9 May 2007 **Reference 2007 / 106**

Appendix 2: Consent Form



Department of Sport and Exercise Science Nico Kurpiers Building 750 Telephone 09 373 7599 extn. 86821

CONSENT FORM

| Project title: | Dynamics of | Free Style | Skiing – | Equipmente | Development | and |
|----------------|------------------|---------------|--------------|------------|-------------|-----|
| | Implications for | r Injury Prev | vention Stra | itegies | | |

Researchers: Nico Kurpiers, PhD Candidate (PhD) Dr. Uwe Kersting, Associate Professor

I have been given and have understood the explanation of this research project and my role as a subject. In particular I have been informed that:

- 1. I may obtain results regarding the outcome of the project upon completion of the study
- 2. I may withdraw myself from this study at any time
- 3. I may withdraw my data within three months of collection.
- 4. My personal information and my identity will remain confidential
- 5. A video tape will be made of my performance
- 6. Data collected may be used for future studies. Data will be stored on password protected computers. Written information will be stored in a locked filing cabinet in the Department of Sport and Exercise Science. Access will only be granted to the Principal Investigator and Student.
- 7. If I am an enrolled student at the University of Auckland the participation or refusal of participation in this study will not affect my grades in any way.

I agree to take part in this research.

Signed: _____

Name (please print): _____

Date : _____

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE on 9 May 2007 for a period of 3 years, from 9 May 2007 **Reference 2007 / 106**

Appendix 3: General Questionnaire



Department of Sports and Exercise Science Nico Kurpiers, PhD candidate Room 718, Building 750 Telephone 373 7599 extn. 86561

Project title: Dynamics of Freestyle Skiing – Equipment Development and Implications for Injury Prevention Strategies

QUESTIONNAIRE

| Participant #: | Age: | years | |
|---|-----------------------------------|----------------|--------|
| Gender: M / F | Skiing experience: | y | /ears |
| Body height:cm | body weight: | kg | |
| shoe size: | | | |
| 1. Current training status: (all spo | orts you currently participate in | n on a regular | basis) |
| Main sports (1): | / hours per week: | competitive: | Y / N |
| Minor sports (2): | / hours per week: | competitive: | Y / N |
| Minor sports (3): | / hours per week: | competitive: | Y / N |

Minor sports (4): _____ / hours per week: ____ competitive: Y / N

Minor sports (5): _____ / hours per week: ____ competitive: Y / N

2. **Previous training** (all sports you used to train for on a regular basis but did not continue with):



Medical History

3. Have you suffered a major injury (absence from training for more than 3 weeks) within the last three years (Give the year, type of injury and the time away from training as precise as possible)?

4. Do you have any illness/ health problems which may limit your participation in this experiment? (e.g. asthma, heart problems). If so give details.

5. Are you currently taking any prescription medicine? If so give details.

6. Have you ever suffered from a knee injury? If so explain: type, severity, location, time spent in recovery.

| Skiing Related | Questions | | | |
|--|---|---|---|---|
| 7. What type of | of skier would you de | scribe your self a | s? (circle one answ | er) |
| (think about | what you spend mo | st of your skiing t | time practicing) | 1 |
| | | | | |
| Moguls f | reestyle/park rider | free-riding | back country/hiki | ng normal |
| | | siopes | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| 8. When skiin | y how often do you r | erform aerial ma | noeuvres/jumps? (c | ircle one) |
| 8. When skiin | g how often do you p | erform aerial ma | noeuvres/jumps? (c | ircle one) |
| 8. When skiing never | g how often do you p sometimes | erform aerial ma often r | noeuvres/jumps? (c nost runs on | ircle one) all runs |
| When skiing never When skiing | g how often do you p sometimes g how often do you p | often n often n | noeuvres/jumps? (c nost runs on chnique? (circle one | ircle one) all runs |
| When skiing never When skiing | g how often do you p sometimes g how often do you p | often n often n | noeuvres/jumps? (c nost runs on chnique? (circle one | ircle one) all runs e) |
| When skiing never When skiing never | g how often do you p sometimes g how often do you p sometimes | often n often n perform mogul teo regularly | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can | ircle one) all runs e) on all runs |
| When skiing never When skiing never 10. On a scale of | g how often do you p sometimes g how often do you p sometimes | often n often n perform mogul tec regularly you rate your ski | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can | ircle one) all runs e) on all runs |
| When skiing never When skiing never On a scale of (circle approximation) | g how often do you p sometimes g how often do you p sometimes of 1 to 10 how would opriate answer; 1 – p | often n often n often n perform mogul tec regularly you rate your ski oor, 10 – exceller | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can iing ability? nt) | ircle one) all runs e) on all runs |
| 8. When skiing never 9. When skiing never 10. On a scale of (circle approximation) | g how often do you p sometimes g how often do you p sometimes of 1 to 10 how would opriate answer; 1 – p | often n often n perform mogul teo regularly you rate your ski oor, 10 – exceller | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can iing ability? nt) | ircle one) all runs e) on all runs |
| 8. When skiing never 9. When skiing never 10. On a scale of (circle approximation) | g how often do you p sometimes g how often do you p sometimes of 1 to 10 how would opriate answer; 1 – p 1 2 3 4 | often n often n perform mogul teo regularly you rate your ski oor, 10 – excellen 5 6 7 | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can iing ability? nt) 8 9 10 | ircle one) all runs e) on all runs |
| 8. When skiing never 9. When skiing never 10. On a scale of (circle approx 11. What ski let | g how often do you p sometimes g how often do you p sometimes of 1 to 10 how would opriate answer; 1 – p 1 2 3 4 ngth do you usually r | often n often n often n oerform mogul teo regularly you rate your ski oor, 10 – excellen 5 6 7 ide? | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can iing ability? nt) 8 9 10 | ircle one) all runs e) on all runs |
| 8. When skiing never 9. When skiing never 10. On a scale of (circle approximation) 11. What ski lend | g how often do you p sometimes g how often do you p sometimes of 1 to 10 how would opriate answer; 1 – p 1 2 3 4 ngth do you usually r | often n often n often n oerform mogul teo regularly you rate your ski oor, 10 – excellen 5 6 7 ide? | noeuvres/jumps? (c nost runs on chnique? (circle one as often as I can iing ability? nt) 8 9 10 | ircle one) all runs e) on all runs |

12. What pole length do you usually use?

_____cm

13. What ski boot brand and model do you usually ride?

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE on 9 May 2007 for a period of 3 years, from 9 May 2007 **Reference 2007 / 106**

Appendix 4: Perception Questionnaire Indoor



THE UNIVERSITY OF AUCKLAND NEW ZEALAND Department of Sports and Exercise Science

Dr. Uwe Kersting

Room 317, Building 734

Telephone 373 7599 extn. 86859

Project title: Dynamics of Free Style Skiing – Equipment Development and Implications for Injury Prevention Strategies

QUESTIONNAIRE

Rate your perception out of 9 for the following aspects of this measurement system compaired to an ordinary ski-binding-system (circle a number)

| (1: worse | 5 : no di | ffere | ence | | 9 : much better) | | | | better) |
|-----------------------|------------------|-------|------|-------|-------------------------|--------|-------|-------|---------------|
| 1) Safety | | _ | | _ | _ | | _ | _ | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 2) Stability on the s | ki | | | | | | | | |
| · · · | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 3) Speed control | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 4) Effects of skiing | movemer | nts | | | | | | | |
| 4.1) Edging | (horizonta | al mo | oven | nents | s: lef | t/ rig | ght) | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 4.2) Absorbi | ng (vertic | al n | nove | ment | ts: be | endiı | ng/ s | traig | htening legs) |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 4.3) Forward | d/ backwa | ard | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 5) Overall perceived | d perforn | nano | ce | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Comments: | | | | | | | | | |
| | | | | ~ - | | | | | |

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE on 9 May 2007 for a period of 3 years, from 9 may 2007 **Reference 2007 / 106**

Appendix 5: Perception Questionnaire Outdoor

THE UNIVERSITY OF AUCKLAND NEW ZEALAND

Department of Sports and Exercise Science Nico Kurpiers, PhD Candidate Biomechanics laboratory Telephone 0064-9-373 7599 extn. 82561

Project title:Dynamics of Free Style Skiing – Equipment Development and Implications for Injury Prevention Strategies

QUESTIONNAIRE

Rate your perception out of 9 for the following aspects for this modified ski boot compared to your ordinary ski-boot (circle a number); say which skiboot you use:

| (1: worse | 5 : no di | ffere | ence | | | | 9 : n | nuch | better) | |
|-----------------------|------------------|-------|-------|-------|-------|--------|--------------|-------|-----------|------|
| 1) Effects on skiing | moveme | nts | | | | | | | | |
| 1.1) Absorbii | ng (vertio | al m | ove | ment | s: be | endir | ng/ s | traig | htening l | egs) |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1.2) Forward | lean | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1.3) Edging (| horizonta | al mo | oven | nents | : lef | t/ rig | (ht) | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 2) Balance | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 3) Speed control | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 4) Safety | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 5) Overall acceptance | ce as a tr | aini | ng t | ool (| bala | nce | traiı | ning | etc.) | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 6) Overall acceptance | ce as a co | omp | etiti | on sl | si bo | oot | | | | |
| - | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |

Comments (e.g., feeling comfortable or uncomfortable; difference 1st day to last day etc.):

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE on 9 May 2007 for a period of 3 years, from 9 may 2007 **Reference 2007 / 106**

Appendix 6: Sensitivity Analysis – Additional data for shifted force plate

Table 22: Alteration for selected parameters in percentage for shifted force plate of 2 cm, 1.5 cm, 1cm (x,y,z) (LKnIntRotM_Fmax = left knee internal-external rotation moment, LKnvalgM_Fmax = left knee valgus moment, LGastLat = left gastrocnemius, LSolMed = left soleus medialis, LRect = left rectus femoris)

| condition | LKnIntRot | LKnvalgM_F | LGastL | LSolMed | LRect |
|---------------|-----------|------------|--------|---------|-------|
| | M_Fmax | max | at | | |
| Post-prox-lat | -20 | -12 | 25 | 4 | 2 |
| Post-prox-med | 22 | 54 | 35 | 8 | 3 |
| Post-dist-lat | -43 | -35 | 28 | 5 | 1 |
| Post-dist-med | 5 | 33 | 38 | 9 | 2 |
| Distal | -11 | -14 | 2 | 0 | -1 |
| Proximal | 9 | 11 | -2 | 0 | 1 |
| Psterior | -7 | 10 | 31 | 7 | 2 |
| Anterior | 1 | -17 | -43 | -6 | -2 |
| Lateral | -28 | -41 | -6 | -2 | 0 |
| Medial | 20 | 30 | 6 | 2 | 0 |
| Neutral | 0 | 0 | 0 | 0 | 0 |
| Ant-prox-lat | -15 | -41 | -52 | -8 | -2 |
| Ant-prox-med | 34 | 25 | -37 | -4 | -2 |
| Ant-dist-lat | -37 | -70 | -48 | -8 | -3 |
| Ant-dist-med | 19 | 7 | -34 | -4 | -3 |

Appendix 7: Sensitivity Analysis – Additional data for shifted markers

Table 23: Alteration for selected parameters in percentage for shifted markers of 2 cm in x,y,z direction (RKnIntRotM_Fmax = right knee internal-external rotation moment, RKnvalgM_Fmax = right knee valgus moment, RGastLat = right gastrocnemius, RSolMed = right soleus medialis, RRect = right rectus femoris).

| Condition | RKnIntRotM Fmax | RKnvalg M Fmax | Rgast_F max | Rsol Fmax | Rrect Fmax |
|----------------------------|--------------------|-------------------|----------------|-----------|------------|
| Shortreference | 0 | 0 | 0 | 0 | 0 |
| AnkleXplus2 | -5 | 8 | 0 | 0 | 3 |
| AnkleXminus2 | -26 | 14 | 0 | 0 | 2 |
| KneeXplus2 | -16 | 19 | 0 | 0 | 3 |
| KneeXminus2 | -17 | 19 | 0 | 0 | 2 |
| Knee&ankleXplus2 | -5 | 8 | 0 | 0 | 3 |
| Knee&ankleXminus2 | -26 | 14 | 0 | 0 | 2 |
| KneeXplus2ankleXmi nus2 | -26 | 14 | 0 | 0 | 2 |
| KneeXminus2ankleXp | | | | | |
| lus2 | -26 | 14 | 0 | 0 | 2 |
| KneeZplus2 | -33 | 22 | 0 | 0 | 5 |
| KneeZminus2 | 0 | 0 | 0 | 0 | 0 |
| RightKneeXplus2 | -16 | 19 | 0 | 0 | 3 |
| RightKneeXminus2 | -16 | 19 | 0 | 0 | 3 |

Appendix 8: Sensitivity Analysis – Additional data for tilted force plate

Table 24: Alteration for selected parameters in percentage for tilted force plate of 5 degrees (LKnIntRotM_Fmax = left knee internal-external rotation moment, LKnvalgM_Fmax = left knee valgus moment, LGastLat = left gastrocnemius, LSolMed = left soleus medialis, LRect = left rectus femoris)

| condition | LKnIntRotM Fmax | LKnvalgM Fmax | Lgast Fmax | Lsol Fmax | Lrect Fmax |
|----------------|--------------------|---------------|------------|-----------|------------|
| shortreference | 0 | 0 | 0 | 0 | 0 |
| Xplus5grad | 28 | -96 | 98 | -15 | -4 |
| Xminus5grad | -56 | 116 | 98 | -15 | 20 |
| Yplus5grad | -25 | 11 | 98 | -16 | -8 |
| Yminus5grad | -11 | 0 | 98 | -14 | 26 |
| Zplus5grad | -7 | -5 | 98 | -15 | 11 |
| Zminus5grad | -7 | -5 | 98 | -15 | 11 |

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