University of Salzburg

Department of Sport Science and Kinesiology

Biomechanical Aspects of Performance Enhancement and Injury Prevention in Alpine Ski Racing

Doctoral Thesis

Fulfilment of the Requirements for the Doctoral Degree in Natural Science (Dr. rer. nat.)

Submitted by:

Jörg Spörri

Reviewed by:

Univ. Prof. Dr. Erich Müller

Univ. Prof. Dr. Hermann Schwameder

Salzburg, December 2012

I. Acknowledgements

“Coming together is a beginning; keeping together is progress; working together is success.” Henry Ford

It is a privilege to have the opportunity to write a doctoral thesis on a topic of highest intrinsic motivation, as it has been the case for my thesis. However, it is even a higher privilege to find people who share this passion with you. There are numerous individuals I would like to thank for their outstanding contributions to my dissertation-project.

First, and foremost, I would to thank my beloved wife, Sonja, and my wonderful parents, Alice and Otto, for their patience and support during my dissertation-project. They were my retaining wall all over the years.

Second, I would like to express my sincere gratitude to my co-worker Dr. Josef Kröll for all the exciting discussions and his very important contributions to my dissertation-project. In him, not only did I find a good friend, but also a like-minded peer with the same passion for alpine ski racing research.

A special thank you goes to my head-supervisor Prof. Dr. E. Müller for giving me the chance to realise a dissertation-project in a field of highest personal interests. From the very beginning he shared my enthusiasm for this very interesting topic and paved the way for its investigation. I also would like to thank my co-supervisors Prof. Dr. H. Schwameder and Prof. Dr. G. Amesberger for their constructive inputs and inspiring ideas while realizing specific project-parts and publications of my dissertation-project.

Last, but not least, I would like to thank all other people which were directly or indirectly involved in one or several project-parts and made the realisation of this doctoral thesis possible.

Salzburg, December 2012

II. Abstract

Competitive alpine ski racing is a spectacular and fascinating sport attracting the public interest. For many decades, substantial efforts have been undertaken to enhance the athlete's performance by various players, such as national sport federations and equipment suppliers. As a consequence of exploring the limits of the sport, the incidence and severity of injuries have been become alarmingly high. From previous studies it is known that more than one third of the World Cup (WC) athletes are injured each season, and that up to 72 per cent have sustained at least one severe injury during their careers.[1, 2] Even though in recent years significant efforts have been made to reduce these injuries, preventive measures are still not as effective as they could be. This is due to the fact that the causes of injuries are still not well understood and the knowledge about the influence of potential prevention strategies on biomechanical variables related to injury risk is still poor. With respect to performance enhancement, there is a similar situation: even though alpine ski racing is a highly developed sport in terms of business, equipment, and training concepts, there is still a lack of functional and biomechanical understanding of the performance relevant factors. This lack of knowledge often leads to a situation that performance enhancement is only achieved occasionally by the principle of "trial and error". Hence, there is an evident need for a more detailed understanding of biomechanical aspects related to performance enhancement and injury prevention in alpine ski racing.

Therefore, this thesis has three main purposes: (1) to assess current performance prediction/enhancement concepts used in science and/or coaching; (2) to compile and to explore perceived key injury risk factors; and (3) to assess the potential injury prevention strategy of increasing the horizontal gate distance in order to reduce speed. For these purposes a video-based 3D kinematic field measurement with a top world class athlete and explorative qualitative interviews with expert stakeholders were conducted.

Regarding the first purpose, it was found that none of the existing performance prediction/enhancement concepts were able to entirely explain time differences between different performed turns of a top world class athlete. This might be explained by the fact that these concepts address only isolated aspects of ski racing performance. Hence, for both science and coaching, there is a need for more comprehensive approaches that include all variables influencing performance in one concept. Comparing the characteristics of fast and slow turns, it was found that the skier's line and timing played a major role for time over short sections. Fast turns were initiated higher regarding the vertical position on the slope plane and were turned less out of the direction of the fall line. Concerning the second purpose, a total of 32 perceived risk factors categories were derived from the expert stakeholder interviews within the basic categories Athlete, Course, Equipment and Snow. Regarding their perceived impact on injury risk, the experts' top five categories were found to be: system ski, binding, plate and boot; changing snow conditions; speed and course setting aspects; physical aspects of the athletes; and speed in general. Finally, in relation to the third purpose, it was found that in order to considerably reduce speed by increasing the horizontal gate distances, substantial course setting changes might be needed, since racers are able to adapt and partly compensate by changing their timing strategies. Furthermore, it was found that there might be two safety drawbacks of controlling speed by increased horizontal gate distances: increased fatigue and higher risk of out-of-balance situations.

In summary, this doctoral thesis has added a substantial contribution to the current body of knowledge and provided more detailed hypotheses for further studies that are based on both scientific indication and stakeholders' knowledge. However, due to the explorative character of this thesis, further studies should verify the plausibility of the findings and investigate the more detailed hypotheses.

III. Abbreviations and Symbols

General Abbreviations

ACL	Anterior Cruciate Ligament
COM	Centre of Mass
DLT	Direct Linear Transformation
FIS	Fédération International Ski
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IOC	International Olympic Committee
WC	World Cup
2D	Two Dimensional
3D	Three Dimensional

Thesis Specific Parameters

d_{vert}	Vertical Distance Ankle-COM
λ_{Lean}	Lean Angle
$d_{Fore/Aft}$	Fore/Aft Position
γ_{Ski}	Skid Angle
L_{COM}	COM Path Length
R_{COM}	COM Turn Radius
β_{COM}	COM Traverse Angle
v_{COM}	COM Velocity
$\Delta e_{mech}/v_{in}$	Difference in Mechanical Energy divided by Entrance Velocity
F_{cp}	Relative Centripetal Force

IV. Table of Contents

1 Introduction

1.1 Background

1.1.1 History of Alpine Ski Racing

The following landmarks of alpine skiing history are based on the work of Polednik [3], Suttner [4] and Lauterwasser et al. [5], as well as on information on the websites of the International Ski Federation (FIS) [6], the FIS Ski-Museum Vaduz [7], and the International Olympic Committee (IOC) [8]:

The history of alpine skiing goes back over 6000 years (Figure 1). Prehistoric wall paintings and fragments of antique skis found from that time document the heritage of skiing around 4000 B.C. In the very beginning, skis were mainly used by hunters for an efficient change of location in snow-covered areas. Later, from 1200 AD on, skis were used for military purposes and battles. In this context, even long distance travels across Europe were reported (1517 AD). First descriptions of skiing techniques were published in military manuals around 1765 AD.

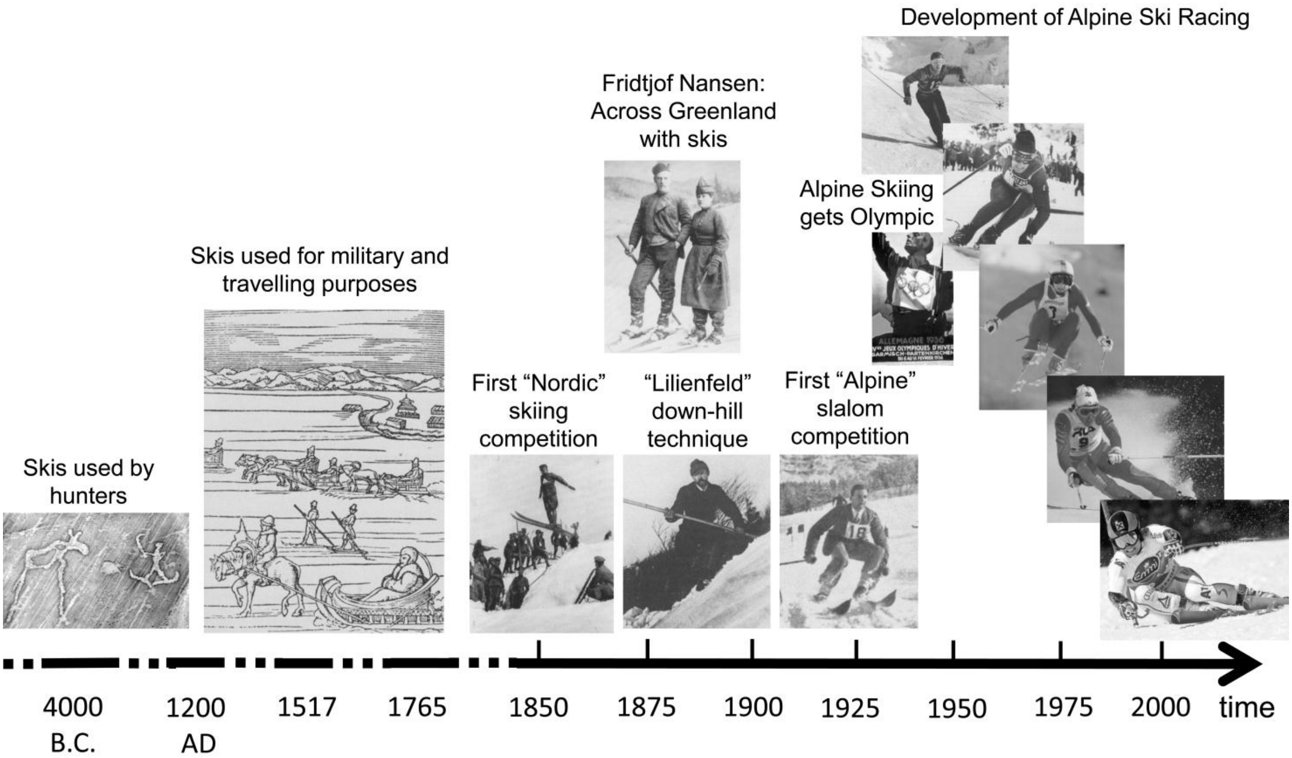


Figure 1: Landmarks of skiing history. (own illustration based on the work and pictures of Polednik [3], Suttner [4] and Lauterwasser et al. [5], as well as on information on the websites of the International Ski Federation (FIS) [6], the FIS Ski-Museum Vaduz [7] and the International Olympic Committee (IOC) [8]).

Despite the very long history of skiing, its sportive and competitive facet is quite "new". The first skiing competitions were organized in Norway around 1850 AD by officers, students and countrymen. Originally, only jumping and cross-country competitions ("Nordic" disciplines) were carried out, while downhill skiing was not a competitive discipline at that time. The rapid popularity gain of skiing as a sport spread from Scandinavia to the alpine countries in the 1870´s. The first popularity peak was reached in the 1890´s when the book of Fridtjof Nansen about his journey across Greenland was published. At the same time, in the alpine countries, the first ski clubs were established. An interesting aspect is the fact that originally the Alps were not believed to be suitable for skiing, since in order to break, the “Nordic” style of skiing required a flat and smoothly running out terrain. Consequently, during the time of the first attempts to ski in the Alps it was common to hike up the mountain by using skis and to descend without skis. However, over time more and more skiers reached the high alpine terrain and a new style of downhill skiing, “Alpine skiing” was developed. A milestone of this development was the publication of the teaching manual “Lilienfelder Skilauftechnik” in 1896 AD. This comprehensive manual suggested novel skiing techniques for steep and difficult descents.

The first alpine skiing competition took place over 25 years later, in 1922 AD, in Mürren. Then, in 1924 AD, the International Ski Federation (FIS) was established, and in 1936 AD, alpine ski racing was included in the Olympic program. From the 1940`s onwards, there was a constant development of competitive skiing in terms of business and coaching concepts. The most significant development to alpine ski racing likely occurred in the 1990`s with the introduction of the carving skis and binding plates. These changes enabled racers to reach even higher inclination angles and to carve tighter turns, which changed the appearance of the sport significantly.

1.1.2 What is Alpine Ski Racing?

Alpine ski racing, as it is known today, is a spectacular and fascinating sport. Basically, it consists of four disciplines, namely, slalom, giant slalom, super-g and downhill, which differ primarily in speed and the course/equipment regulative.[9] In addition, combined and team disciplines exist. The best racers in the world compete at the FIS World Cup (WC) circuit. Major events, such as the WC races in Kitzbühel, are public magnets attracting up to 100,000 spectators along the course.[10] Live TV-broadcasts and TV-reports of such events reach up to 262 million people.[10] Hence, these events not only generate high transaction volumes, but might also have sustainable effects on the image of associated brands or destinations.

Facing these medial and therefore, economical dimensions, and knowing that only the best athletes are attractive for sponsors, it is understandable that there is an enormous interest in performance enhancement by various players, such as national sport federations and equipment suppliers (Figure 2). National sport federations aim for developing competitive athletes; equipment suppliers aim for competitive equipment. Moreover, WC competition organizers, led by the FIS Race Directors, aim for spectacular, fair and safe course and snow conditions. However, performance and/or business enhancement strategies often do not meet safety efforts. Hence, conflicts of interest are inescapable and it is a major challenge for all involved players to keep the balance between performance and injury related aspects of alpine ski racing. In this context, the international competition rules and their executing body “FIS”, take over a governing function in the sport of alpine ski racing.

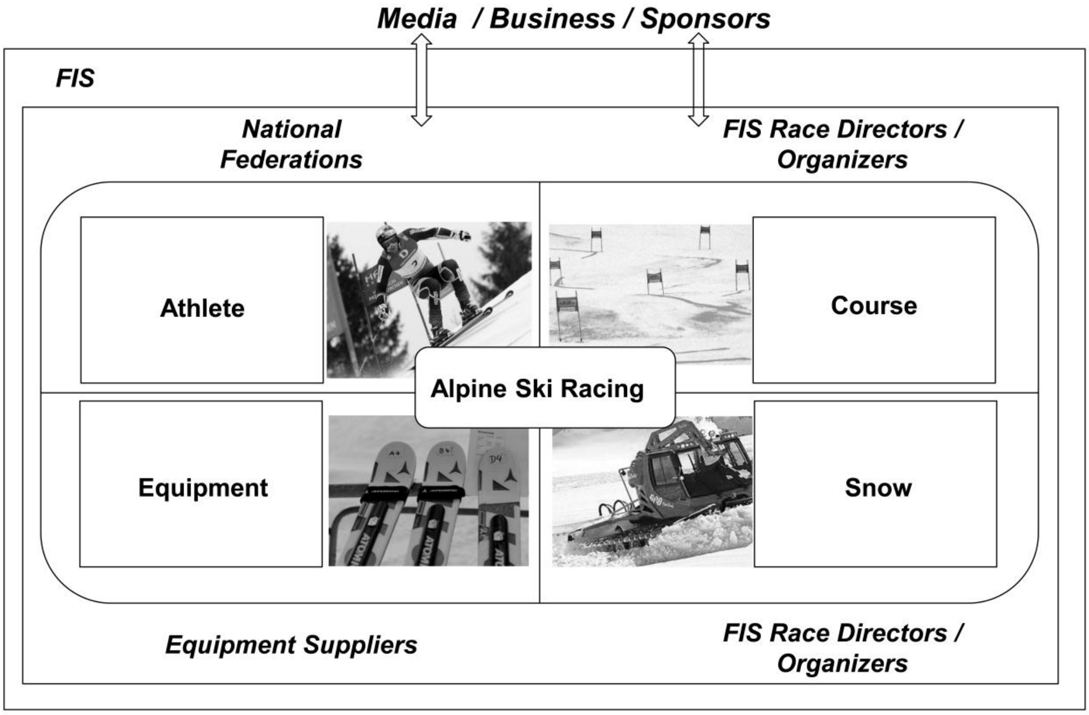


Figure 2: What is alpine ski racing: a comprehensive overview (own illustration).

In the sport of alpine ski racing, two central aspects are the athlete`s technique and tactic (choice of line). From a theoretical point of view, the skier’s technique can be quantified by four key movement components: vertical, lateral, fore/aft and rotational (Figure 3). They are the result of specific partial body movements and are characterized by the various joint angles. The skier`s vertical movement component is mainly depending on the joint angles of the lower body and has a direct effect on the weighting and un-weighting of the skis.[11] The skier`s lateral movement component is, together with hip- and knee- angulations, mainly responsible for the edging of the ski.[12-14] The skier`s movement component in the fore/aft direction has a direct influence on the pressure distribution on the ski, and therefore, on the bending line of the ski.[11] The sum of all rotational movements manifests in the ski axis orientation with respect to the instant direction of motion. This angle of divergence can be seen as an estimation of the degree of skidding.[15]

The skier’s line can be quantified by five variables describing the placement of the turn, the instant direction of motion, as well as the path and timing characteristics (Figure 3). The placement of the beginning and end of the turn can be quantified by the positions of the crossing points of centre of mass (COM) line and ski line projected to the slope plane.[16] The skier’s instant direction of motion can be described by the instantaneous angle between the direction of motion and the direction of the fall line (traverse angle).[17] The path between the beginning and end of the turn can be characterised by the path length and the curvature of the path (turn radius).[14] The timing within the turn can be quantified by the percentage of each turn phase on the whole turn cycle, called turn cycle structure.[14]

Finally, the skier`s technique and line are directly related to the skier’s energy and loading patterns (Figure 3); two essential factors in the context of performance and injury related aspects.

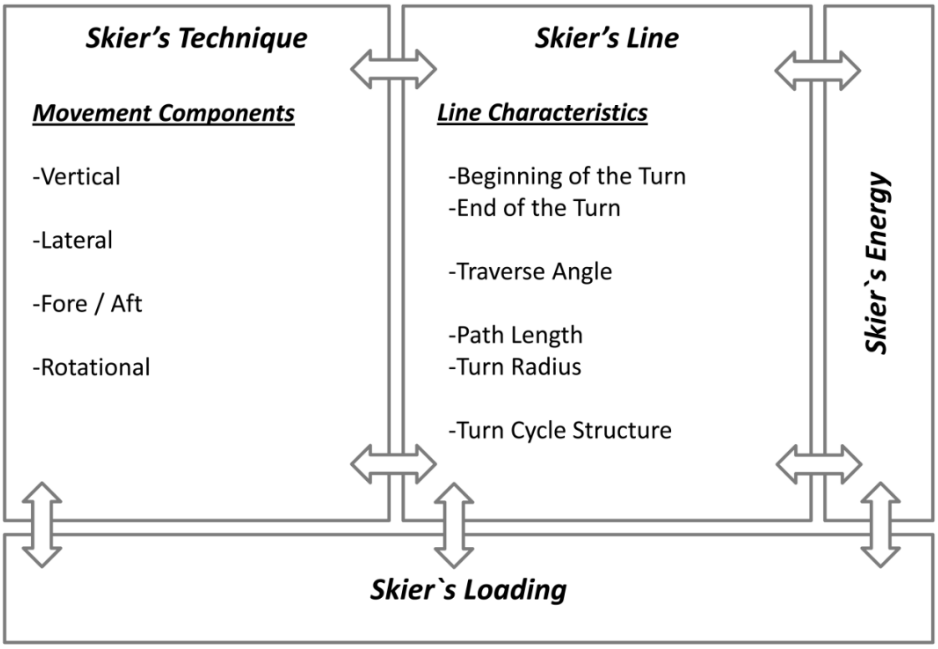


Figure 3: The characterisation of the skier's technique and line (own illustration).

1.2 Investigation Problems

1.2.1 Performance Related Aspects of Alpine Ski Racing

In competitive sports, reaching high performance is the base of any success. However, depending on the sport, the discipline and the specific competition, performance can have different meanings: short time, long distance, high speed, high score or high target accuracy. In alpine ski racing, performance is defined by competition rules as the shortest time from the start to the finish line of a predefined race course.[9] Hence, by definition a skier`s overall performance depends on the skier`s performance within the various sections of the course. However, it has to be pointed out that a high (instantaneous) performance within one section is not automatically advantageous for the overall performance.[18] Due to tactical reasons, in some cases even a lower instantaneous/section performance can be beneficial if it results in a disproportionally higher performance in the following section. Nevertheless, information about instantaneous/section performance can be very useful for the purpose of performance enhancement, since for shorter sections, external disturbances (wind, changing snow conditions, technical mistakes and tactical manoeuvres of the skier) are easier to control during test measurements.

Status Quo of Literature:

How to Enhance Sport Performance?

Sport performance depends on a variety of interacting factors: (1) athlete related factors, such as physical, psychological, technical and tactical skills, as well as anthropometric and genetic predispositions;[19] (2) equipment related factors, such as the construction, setup and preparation of the sport equipment components;[20] and (3) competition related factors, such as weather, ground/

floor conditions, terrain/course, and competition rules.[14] In this context, it is remarkable that in various sports time differences among top-level athletes are often only hundredths of a second.

Since the competition related factors are given constraints, literature of performance enhancement in sport is mainly focused on athlete and equipment related aspects, as the example of alpine ski racing shows:[21-29] (1) systematic training and coaching strategies seek to increase the athletes' physical, psychological, technical and tactical skills and (2) continuous equipment development and testing processes seek to increase the general equipment performance. A major challenge for the enhancement of both athlete and equipment performance is the fact that in field sports such as alpine ski racing, external constraints may vary between and within competitions. Depending on the specific conditions (course setting, terrain, snow temperature/humidity and snow preparation), there might be additional demands on the athlete and/or equipment. This makes it very difficult to understand the factors underlying performance, which is an essential pre-step for the prediction/enhancement of performance. As a consequence and due to the complexity of the variables influencing performance, most of the sports performance prediction/enhancement concepts are focused on isolated aspects of performance.

Performance Enhancement Research in Alpine Ski Racing

Reviewing the current literature of performance enhancement with respect to the athlete related aspects of technique and tactics, it is surprising how unbalanced the proportion between practical and scientific approaches is. While there has been a wide spectrum of articles and manuals based on "coaching experience" available for many decades, there is only a limited number of scientific papers dealing with competitive skiing. In scientific publications the main discussed points regarding skiing performance are: the air drag,[30-33] the skier's technique,[14, 20, 23, 26, 34-39] the skier's line,[13, 24, 40, 41] and the skier's mechanical energy.[18, 42, 43]

Aerodynamic drag has been suggested to play an important role for the performance of athletes in high velocity motion sports.[30-33] The aerodynamic drag is mainly dependent on the skier's posture (frontal area / shape / surface) and the skier's speed.[30] The differences in aerodynamic drag between dynamic postures and compact postures in giant slalom have been shown to be as much as 10%.[31] Since the aerodynamic drag is one factor influencing the skier's mechanical energy,[43] compact postures are suggested as a general performance enhancement approach.[30] However, compact postures may negatively affect the function of the skier's movement components. Moreover, in giant slalom the influence of ski friction has been shown to be more important than the influence of aerodynamic drag.[31, 33]

The skier`s technique is related to the overall performance on two counts: first, by interacting with the equipment, the skier's movement components have a major influence on the skier's line [41] and on the skier's mechanical energy.[23] Second, a stable technique is the main fundament for staying in dynamic equilibrium and avoiding mistakes.[11] Since the correction of mistakes normally results in considerably higher friction, overall performance might be negatively affected as well.

The skier`s line is related to the overall performance, since the skier´s choice of line directly influences the path length and the balance between instant acceleration and deceleration. The accelerating component of gravitational force primarily depends on the angle between the direction of motion and the direction of the fall line: the smaller the angle, the higher the acceleration.[13] This fact opens the opportunity for a tactical optimization regarding the choice of line: similar to the "brachistochrone" problem known from physics, the question of when and how potential energy is transformed to kinetic energy has a substantial influence on section performance.[13, 24, 40] Based on these theoretical considerations, a trajectory with a shape similar to the letter Z (strategy "short turning pull out straight") has been suggested to be the path of the quickest descent.[13, 24, 40] Moreover, there is a common coaches' doctrine that a short path length results in better performance. On the other hand, these line characteristics, including a short turn radius, are known to be related to high friction, a factor decreasing performance again.[18, 23, 43]

The skier's mechanical energy is related to performance as follows: starting with a certain amount of entrance velocity and potential energy and following a predefined course, potential energy is transformed into kinetic energy. During this transformation some of the potential energy is lost due to snow friction and air drag. One performance enhancement approach might be to aim for high section exit velocities and, therefore, high entrance velocities for the following sections. On the other hand, this strategy might be limited due to a kind of "velocity barrier" above which the athlete needs to control speed in order to avoid mistakes.[18] Another performance enhancement approach in this context might be to minimise energy dissipation, in particular, friction.[18, 43] In this context, avoiding the shortest turn radii and optimising the skier's action with respect to friction have been suggested in order to increase performance.[18, 23, 26]

Based on the aforementioned body of knowledge, current performance enhancement concepts can be summarised as illustrated in Figure 4. In summary, the main challenge for reaching high performance is to find the best individual and situational compromise of minimising energy losses while following the line strategy of "short turning – pull out straight"; two strategies that contradict each other.

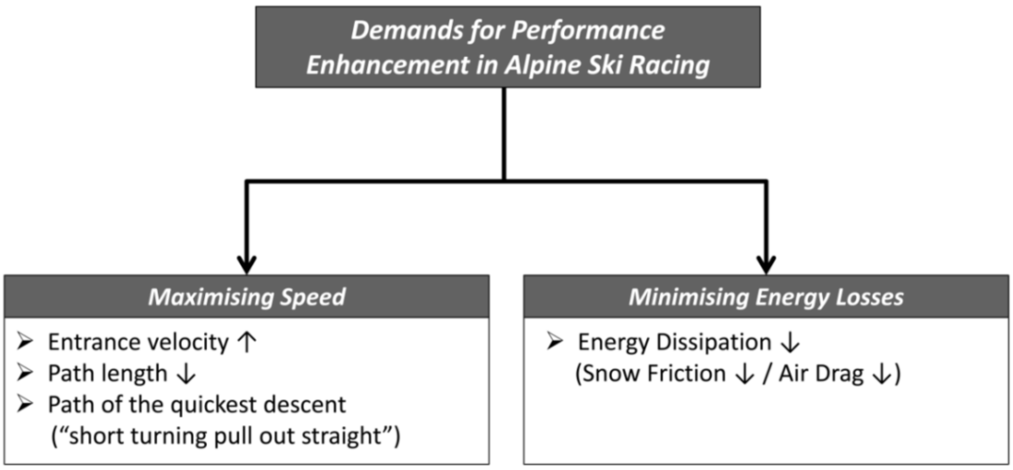


Figure 4: Demands for performance enhancement (own illustration).

Missing Elements in Literature:

Assessment of Current Performance Enhancement Concepts

Based on the body of knowledge described above, various concepts explaining time differences have been suggested in science and/or coaching. Following these concepts, different coaching practices have been developed. However, most of them are focused on isolated aspects of performance, such as the skier's speed or energy state, and might interfere with other important aspects. As described above, some of the concepts actually contradict each other. Hence, there is an evident need for an assessment of performance enhancement concepts common for top level competitive skiing from a global perspective. Moreover, it is not a priori clear which turn characteristics should be aimed for in a specific situation in order to reach a high performance.

1.2.2 Injury Related Aspects of Alpine Ski Racing

At a first glance, alpine ski racing might be associated with well-trained, brave and glorious athletes reaching tremendous speeds while skiing down steep and icy slopes, always having the dream of victory in mind. However, this glamorous public spectacle has another side of the coin as well: injuries. Injuries in WC alpine ski racing are frequent and, compared to other high performance sports, are alarmingly high.[1, 44] Over the last six WC seasons more than one third of the athletes were injured during each season.[1] Even more worrying is the fact that from all recorded injuries more than 30% were severe (> 28 days of absence).[1] Severe injuries may not only hinder the athletes from participating in competitions, but also may increase the risk of re-injury and long term adverse health effects, such as higher prevalence of early osteoarthritis.[45] Hence, there is an evident need to prevent these injuries.

Status Quo of Literature:

How to Prevent Sport Injuries?

How sport injuries can efficiently be prevented often is not obvious at a first glance. Consequently, van Mechelen et al. [46] introduced a four step sequence for injury prevention research (Figure 5). In a first step, the extent of the injury problem should established by monitoring the incidence and severity of the injuries. In a second step, the injury causation should be clarified. Then, once the magnitude and causes of the injury problem are known, potential preventative measure should be introduced, and finally assessed regarding their effectiveness.

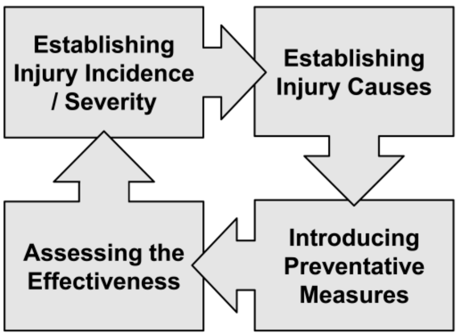


Figure 5: Four step sequence of injury prevention (adapted from van Mechelen et al. [46] & Bahr and Krosshaug [47]).

One of the most challenging steps of this sequence is to establish a complete understanding of the causes of injury.[47] Therefore, a comprehensive model of injury causes (Figure 6) should account for all factors involved: the injury risk factors, as well as a precise description of the events leading to the injury situation and the injury mechanism itself.[47, 48] Even if at first glance, an injury seems to emerge from a single inciting event, the causation of injury is multi-factorial. Intrinsic risk factors, such as age, sex, body composition, or previous injuries, may predispose athletes to injury. In the case of an exposure to certain extrinsic risk factors such as weather/ground conditions, equipment, or competition rules, the athletes become susceptible to injuries. Finally, the inciting event is the last piece in the chain of factors and events leading to the injury.

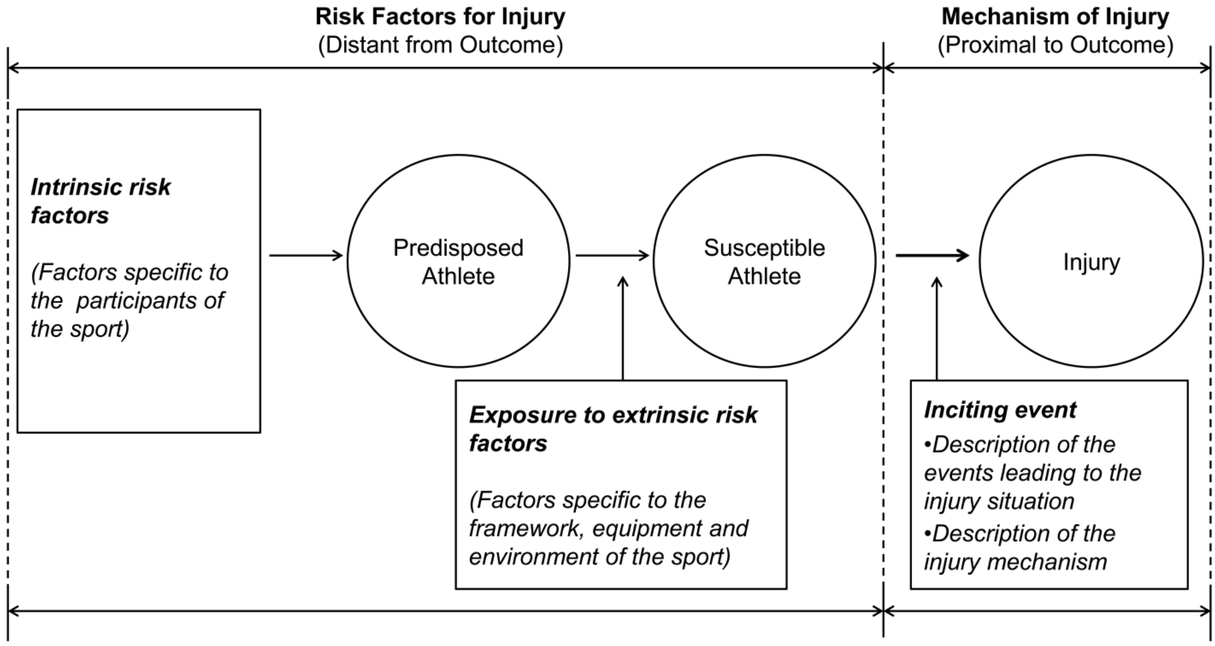


Figure 6: Model of injury causation (adapted from Meeuwisse [48] and Bahr and Krosshaug [47]).

Injury prevention in high performance sports is not only a matter of knowledge, but also a matter of implementation. International sports governing bodies have a responsibility to identify the risks within their sports, as well as to provide guidance regarding the implementation of injury prevention.[49, 50] While these responsibilities are challenging, they are very important aspects. In fact, in the context of risk management, risk communication between researchers, physicians, physiotherapist, athletes, coaches and other stakeholders is probably one of the most important elements.[49] However, injury prevention is not always in line with personal interest regarding performance and business. Therefore, international sports governing bodies need also to supervise the implementation of injury prevention by their competition rules.

Injury Prevention Research in Alpine Ski Racing

Following the framework of injury prevention research, suggested by van Mechelen et al. [46], the aim of this section is to give the reader a general overview of the current body of scientific knowledge with respect to injury prevention in alpine ski racing. For recreational skiing the extent and causes of injuries, as well as potential injury prevention strategies have been well assessed over many years.[51-63] In contrast, there is limited knowledge for elite competitive skiing.[1, 44, 64-66] Regarding step 1 of the sequence by van Mechelen et al. [46], recent data from WC alpine ski racing illustrated an alarmingly high incidence of Anterior Cruciate Ligament (ACL)-injuries.[1] Regarding the causation of these injuries (step 2), recent studies focused on competitive WC alpine skiing provided a deeper understanding of the events leading to the injury situation and the injury mechanisms of the ACL ruptures.[64-66] Most of the ACL-injury mechanisms while turning developed from a technical/tactical mistake, where the athlete initially lost balance inward and backward.[66] Then while trying to regain the grip on the outer ski, the inner edge of either the outer or inner ski abruptly caught the snow.[65] Finally, this sudden catch of the edge forced the flexed knee within less than 100ms into valgus and internal rotation.[64] Based on these findings, factors that contribute to an aggressive ski-snow interaction, high skiing speeds, large forces and critical factors that lead to an out of balance situation were suggested to play a central role for ACL-injury mechanisms.[65]

An aggressive ski-snow interaction may increase injury risk on two counts: first, an aggressive and direct force transmission between ski and snow may increase the self-steering, and therefore, the self-dynamic behaviour of the ski. As a result, there is less room for errors [67] and the athlete is unable to control the skis in out-of-balance situations.[66, 68] Second, an aggressive ski-snow-interaction favours the abrupt catch of the edge,[66] which is a crucial factor for ACL-injury mechanisms while turning.

The existence of high skiing speeds may have an increasing impact on injury risk in three ways. First of all, theoretically, high skiing speeds lead to high total radial forces; therefore, to higher mechanical load of the body.[68] Second, high skiing speeds, and the resulting high kinetic energy, can induce serious injuries in the case of a quick energy conversion during injury mechanisms with or without falls. The magnitude of kinetic energy becomes even more important if the breaking distance is small, as in crashes, because kinetic energy will then be dissipated by force and distance. Third, the injury situation develops rapidly at high skiing speeds and the athlete may have too little time to react and/or correct.[65, 68]

High turn forces may increase injury risk on two counts. First, if the acting forces are at the limit of the physical resources of the athletes, there may be a higher risk for an out-of-balance situation or a fall to occur. The higher risk could be explained by motor control mechanisms. Performing at the physical limitation, the degree of freedom of the motion patterns will be reduced and the joint stiffness will be increased for easier motor control. But this results in decreased manoeuvrability; consequently, decreased stability, because a variability regarding joint movements and segment positions is needed to enhance the perceptual and motor factors involved in maintaining postural stability.[69] Second, in a rapidly developing slip-catch situation of the ski, or during a dynamic snowplough injury mechanism, high radial forces may be transferred on one leg immediately forcing the knee into valgus and internal rotation, as described by Bere et al. [65].

Out-of-balance situations, backward and/or inward, are known as events leading to ACL-injury mechanisms.[64-66] Since the athlete is trained to stay in course after technical mistakes and not to give up, he intuitively tries to regain grip on the outer ski after an out-of balance situation. During this corrective manoeuvre, the abrupt catch of the edge while regaining snow contact may force the knee into a fatal internal rotation and valgus position.

Based on the aforementioned body of knowledge, the demands on potential preventative measures for ACL-injuries in alpine ski racing (step 3) can be summarised as described in Figure 7.

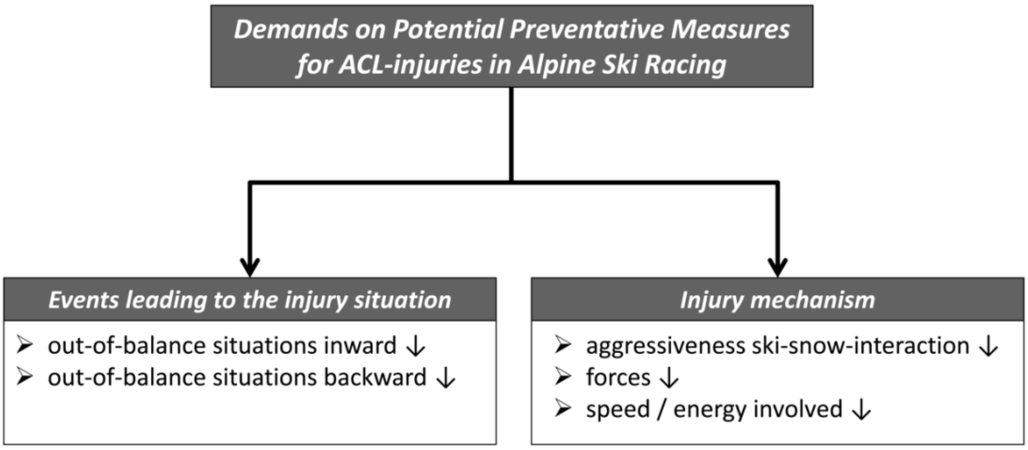


Figure 7: Demands on potential injury prevention measures (own illustration).

Missing Elements in Literature:

Key Injury Risk Factors

Based on the current body of knowledge described above, the factors that make the WC athletes predisposed and susceptible to these injuries (intrinsic and extrinsic risk factors) remain more or less unclear. More knowledge about these factors would be essential in order to be able to define potential preventative measures. Consequently, there is an evident need to investigate intrinsic and extrinsic injury risk factors in WC alpine ski racing.

Assessment of Potential Injury Prevention Strategies

An obvious potential preventative measure is course setting. Course setting is discussed in the ski racing community as a tool to control speed and the energy involved. However, it is not a priori clear whether course setting is able to meet the aforementioned demands on a potential preventative measure. For this reason, it becomes necessary to assess common course setting prevention interventions regarding their effectiveness.

2 Aims of the Thesis

The limitations of the previous research in the field of performance enhancement in alpine ski racing led to the following specific aims for this doctoral thesis:

1. To assess the ability of current performance enhancement concepts to explain time differences within a one turn section.
2. To compare the characteristics of turns with fast and slow section times of top world class athlete and to address the possibility of their being advantageous.
3. To assess whether similar characteristics can be observed for different course settings.

The limitations of the previous research in the field of injury prevention in alpine ski racing led to the following aims for this doctoral thesis:

4. To compile a list of perceived intrinsic and extrinsic key risk factors for severe injuries in WC alpine ski racing, and to explore them in order to provide more detailed hypotheses for further aetiological studies.
5. To investigate the effect of specific course setting modifications as one potential preventative measure on selected biomechanical variables related to injury risk in alpine ski racing.

3 Video-based 3D Kinematics in Field

In the sport of competitive alpine skiing there is a constant change of anatomical landmarks, and therefore, of COM in all three dimensions. In order to analyse the skier`s kinematics with respect to performance and/or injury related aspects, a precise three-dimensional reconstruction of a multi-body segment model of the skier is needed. Therefore, a **"video-based 3D kinematic field measurement"** was conducted for the purposes of this thesis. The aim of the following chapters is to make the reader familiar with the advantages, the methodological procedure, and the limitations of this complex and highly sophisticated measurement method.

3.1 Method Selection

The purpose of this study was to analyse the skier`s three-dimensional (3D) kinematics with respect to functional biomechanical parameters related to performance and injury. This led to the following demands for an appropriate biomechanical measurement method:

- The method should allow a highly accurate reconstruction of anatomical landmarks in 3D, as well as a sufficient precise estimation of COM position.
- The method should represent an established, proven and validated measurement approach for the use of in-field and/or alpine skiing research.
- The method should not interfere with the athlete in any way; he should be able to perform at his limit with his own equipment setup.

Generally, there is a variety of measurement methods that have been suggested to quantify the skier`s kinematics in field: (1) optical systems (infrared-based or video-based 3D kinematics),[14, 18, 34, 37-39, 70-73] (2) Global-Positioning-System (GPS) based systems,[74-78] (3) Inertial-Measurement-Unit (IMU) based systems,[74, 75, 79, 80] and (4) goniometry.[35, 81, 82] Infrared-based systems, such as *VICON (Inc. Vicon Motion Systems, Oxford, UK)*, are known as the gold standard for analysing 3D kinematics of human movement under laboratory conditions. However, their application under field conditions (low temperature, wind, solar radiation, snow spraying) is limited.[70] Moreover, an enormous amount of cameras, up to 24, is needed in order to analyse the capture volume of one ski turn.[70] In contrast, video-based 3D kinematic measurements have been shown to be accurate and applicable under field conditions, in particular for a sufficient precise estimation of COM.[14, 18, 34, 37, 38, 72, 73, 77] In addition, this method implicates only minimal interference with the athlete and enables capture volumes of 1-2 giant slalom turns with only 5-6 panned, tilted and zoomed cameras. Even if wearable systems, such as GPS/IMU-based systems, would allow analysing even wider sections and several turns,[75, 76, 78, 83] they have two major drawbacks with respect to the purposes of this study: (1) they are not validated for use in alpine skiing research, in particular regarding a sufficient estimation of COM, (2) they implicate substantially more interference for the athlete which might hinder him from performing at his limit.

Based on these considerations, "video-based 3D kinematics" was identified as the most appropriate measurement method with respect to the purposes of this thesis.

3.2 Method Description

3.2.1 Overview

On-Hill Setup

The on-hill setup of the video-based 3D kinematic field measurement that builds the fundament for this thesis had the following characteristics. Starting with a middle step section of six gates in order to accelerate up to normal GS speeds, the skier entered the five-gate section presented in Figure 8. Within this section there was a constant slope inclination (27.5°) and constant course set (26m vertical direction with an offset of 10m, respectively 12m). Finally, there was another five gates section in order to avoid tactical manoeuvres of the athletes within the analysed section. Surrounding the section of the analysed turn, cameras were placed on snow platforms with fixed tripods. In order to simulate icy WC-like snow conditions, the slope was prepared with water. Since a major aim of the on-hill setup was that the athlete performs at his limit, total run times were monitored using a commercial chronometry (*Inc. Alge Timing*).

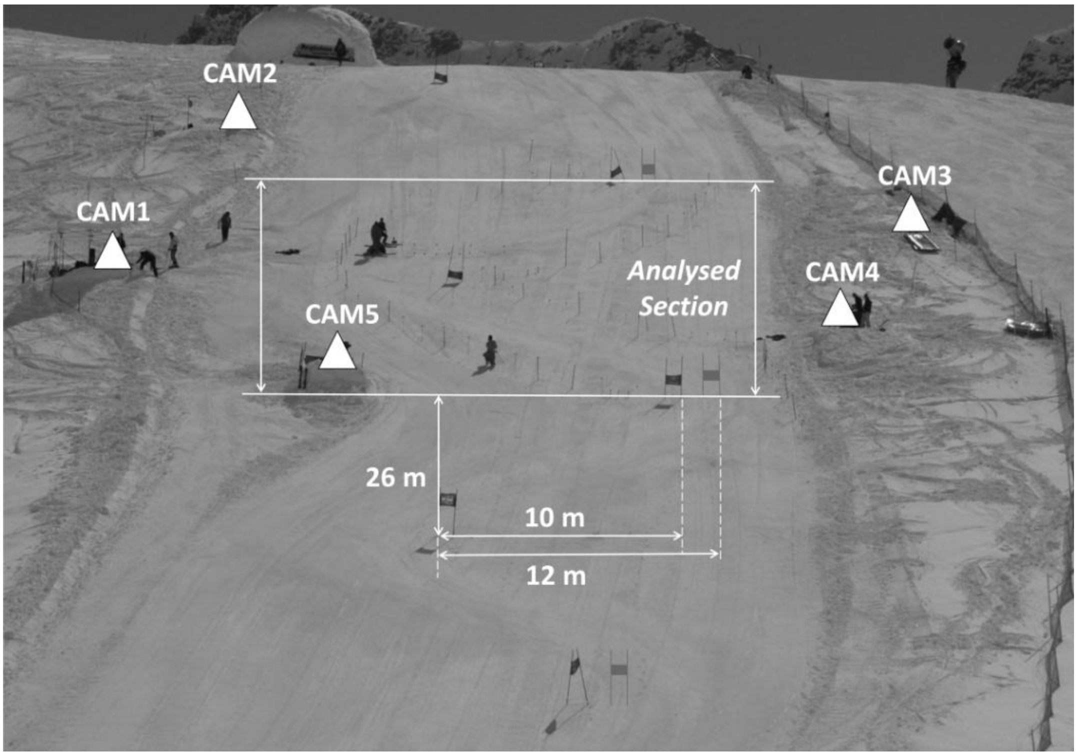


Figure 8: On-hill measurement setup (own illustration; photo: P. Chevalier).

Methodological Procedure

The main steps performed during the video-based 3D kinematics field measurement of the current thesis are summarized in Figure 9. First, a corridor with reference points positioned around the analysed turn was geodetically measured. Second, during motion capture, the skier was filmed by various panned, tilted and zoomed video cameras from different angles. Third, a multi-body segment model and the best visible reference points were manually digitized in each frame of each camera. Fourth, based on the geodetically measured 3D space coordinates of the reference points and the corresponding 2D pixel-coordinates in the video image, the digitised segment model was reconstructed in 3D using a direct linear transformation (DLT)-based Panning Algorithm. Finally, the reconstructed global positions of the anatomical landmarks were post-processed and the specific parameters were calculated.

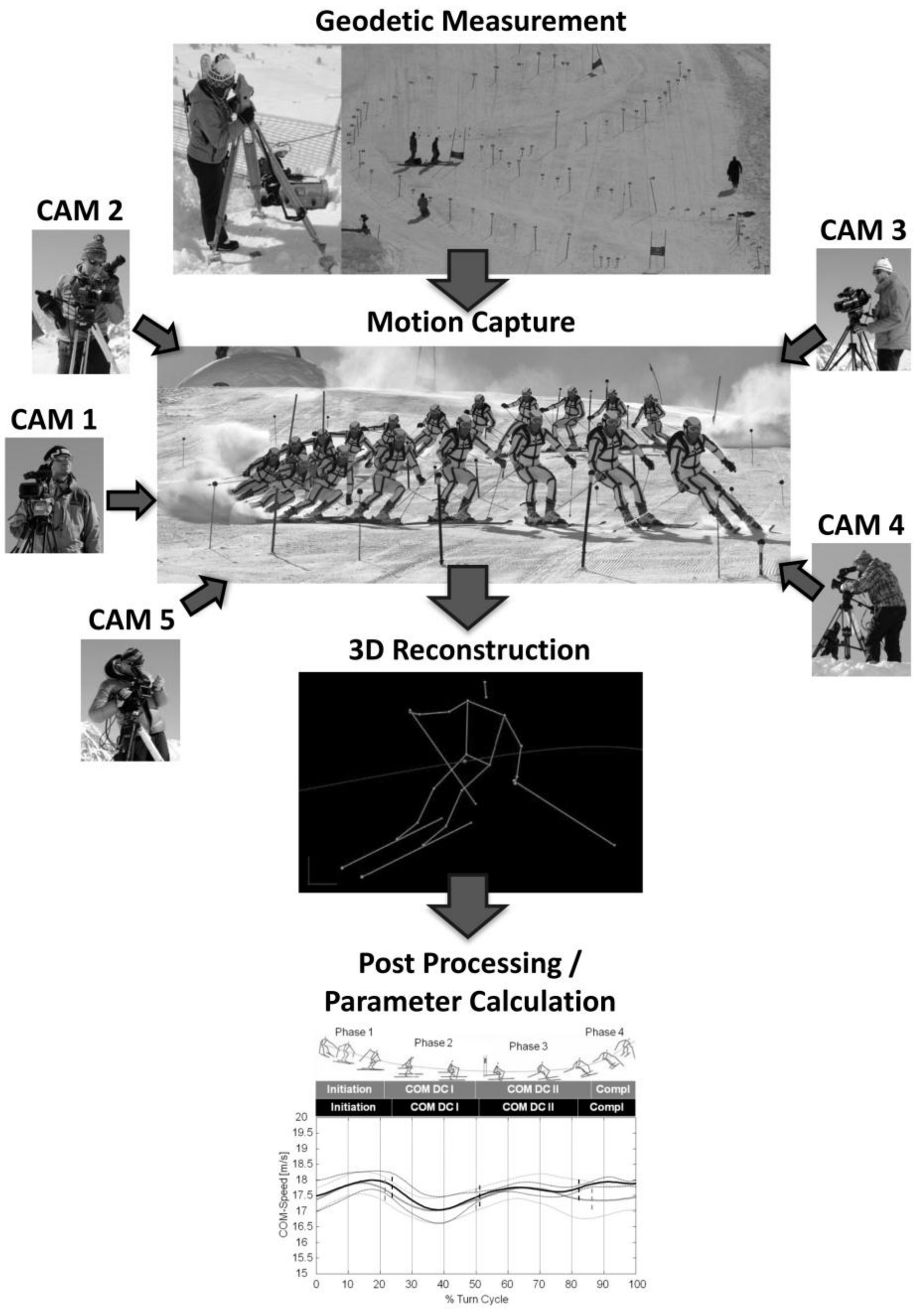


Figure 9: Video-based 3D kinematics – An overview (own illustration; photos: P. Chevalier).

3.2.2 Geodetic Measurement

For analysing the 3D kinematics of a skier in field, large capture volumes are required. Consequently, to be able to track the skier and to keep him in a sufficient size within the camera image, the use of panned, tilted and zoomed cameras is essential.[84] Since panning, tilting and zooming permanently changes the outer and inner orientation of the camera, the spatial coordinates of additional reference points and video cameras are needed in order to keep the cameras calibrated at every instant point in time.[84] For that reason, before and after the motion capture, the 3D space positions of all cameras and reference points were measured geodetically by theodolite *(Tachymeter TCMR 1100 Series, Inc. Leica).*

As additional reference points, black tennis balls mounted on slalom poles of various lengths were used. The number and placement of these points were chosen based on the principle of increasing their visibility and recognisability while decreasing the disturbance of the skier's performance. For the analysis of one giant slalom turn, a total of 78 reference points was required in order to calibrate a capture volume corridor of 52×12×2×m (Figure 10).

Figure 10: Reference point corridor (photo: P. Chevalier).

3.2.3 Motion Capture

During motion capture, the skier was filmed from different angles by five analogue video cameras (*4 Panasonic F15 and 1 Sony UVW-100PL*, 50Hz), time synchronised by a gen-lock signal. Camera positions were defined, as suggested by Drenk [85], in the best compromise the subsequent demands:

1. A clear identification of the anatomical landmarks must be ensured by at least two camera perspectives over the entire capture volume.
2. The optical axes of the cameras used for 3D reconstruction should ideally intersect rectangular over the entire capture volume (Figure 11).
3. The cameras should be positioned as close to the analysed object as possible.
4. Large panning angles should be avoided (max. ≈ 30°).

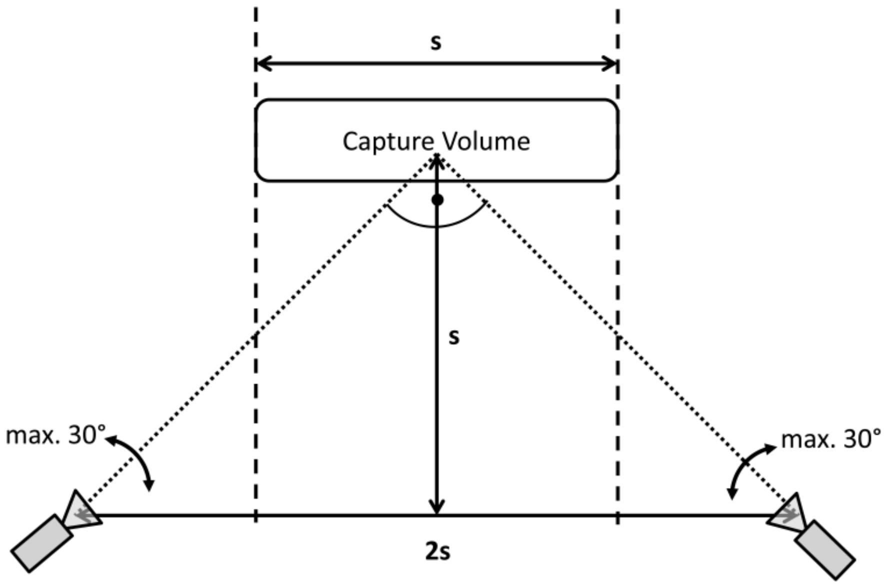


Figure 11: The relation between camera-distance and capture volume size (adapted from Drenk [85] and Regensburger [86])

3.2.4 3D-Reconstruction

Preparation

In the beginning of the 3D reconstruction process, the analogue video capture of each camera was transformed into digital ".avi"-files. Then the video capture of each camera was cut into 1-trial sequences, time synchronised with the corresponding sequences of the other cameras. Following, all five video sequences of a specific trial were imported to the 3D video analysis software *Peak Motus (Version 9, Inc. Vicon Motion Systems)* and attached to a 3D-trial template.

Manual Digitising

In the software *Peak Motus*, a body segment model as well as the three best visible reference points were manually digitised in each frame of each camera for each trial (Figure 12). In order to minimise the errors of manually digitising, the following measures were applied: (1) the athletes were wearing special segment model suits simplifying the determination of the anatomical landmarks; (2) each anatomical landmark was digitised frame by frame over the entire trial, before starting with the next landmark. This allows a smoother digitising of the landmarks over time;[14] (3) the final passage of manual digitising was done by one person only. This was essential in order to reduce the inter-subjective variability in digitising anatomical landmarks.

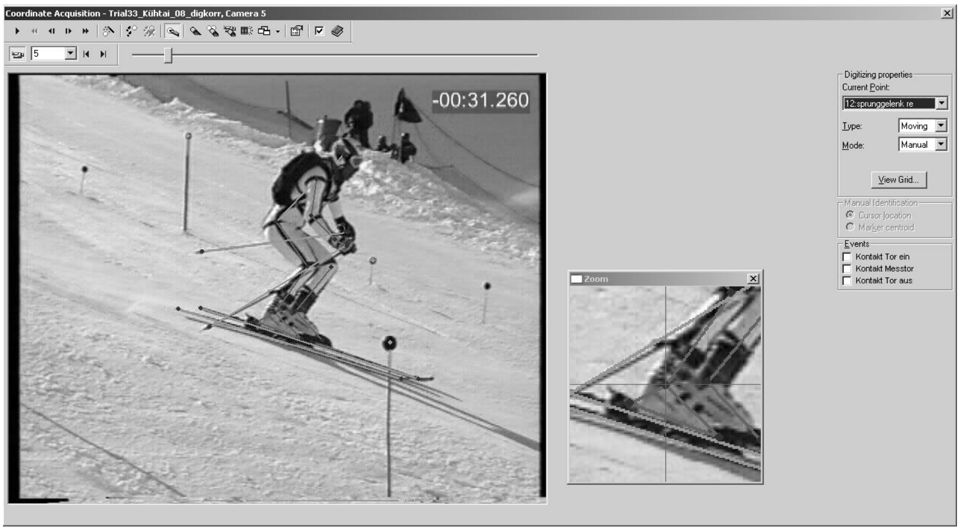
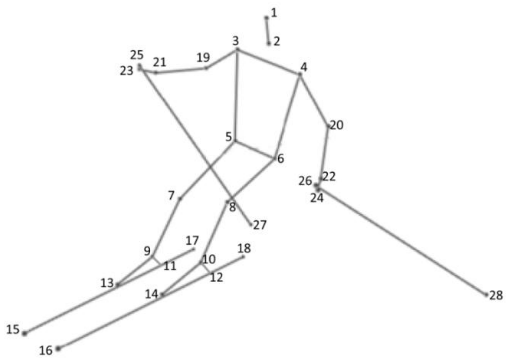


Figure 12: Manual digitising of the body segment model and reference points (screen shot *Peak Motus*).

Segment Model

For the current thesis a 28-point multi-segment body model, representing the skier, the skis and the ski poles, was used (Figure 13). Joint centres of the segment model were determined according to de Leva [87] (see Appendix).



Digitized Points		
1. Head	11. Binding back right	21. Wrist right
2. Neck	12. Binding back left	22. Wrist left
3. Shoulder right	13. Binding front right	23. Hand middle right
4. Shoulder left	14. Binding front left	24. Hand middle left
5. Hip right	15. Ski tip right	25. Stick up right
6. Hip left	16. Ski tip left	26. Stick up left
7. Knee right	17. Ski tail right	27. Stick below right
8. Knee left	18. Ski tail left	28. Stick below left
9. Ankle right	19. Elbow right	
10. Ankle left	20. Elbow left	

Figure 13: The digitized points and the resulting segment model including the equipment (own illustration).

3D Reconstruction

Traditional Photogrammetry (static, metric cameras)

Using traditional photogrammetric measurement methods with metric cameras, the cameras' inner orientation (parameters of the imaging process, such as focal length, lens distortion, principal point coordinate) and outer orientation (camera position in space and its view direction) must be known.[88] If this information is available, the cameras are calibrated and the 3D positions of the anatomical landmarks can be calculated based on already 2 camera perspectives. However, a direct measurement of the inner and outer orientation of the cameras is complex and error-prone.

DLT-Method (static, non-metric cameras)

In contrast, using the method of direct linear transformation (DLT), suggested by Abdel-Aziz and Karara [89], the inner and outer orientation of a camera can be calculated based on reference points with known positions. This method allows the use of standard video cameras, which were not priory calibrated for the use of measurement; a fact enabling the use of photogrammetry in a wider field of application. The DLT-Method is a mathematical transformation between a point in a two-dimensional comparator coordinate system [u,v], in this case the digitised point in the 2D video image, and the real 3D space coordinates of the corresponding point [x,y,z] (Figure 14). The transformation is dependent on the position and orientation of the camera, characterised by the 11 DLT-camera constants ($L_1 \dots L_{11}$). The two linear DLT-equations are:[89]

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1} \qquad v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1}$$

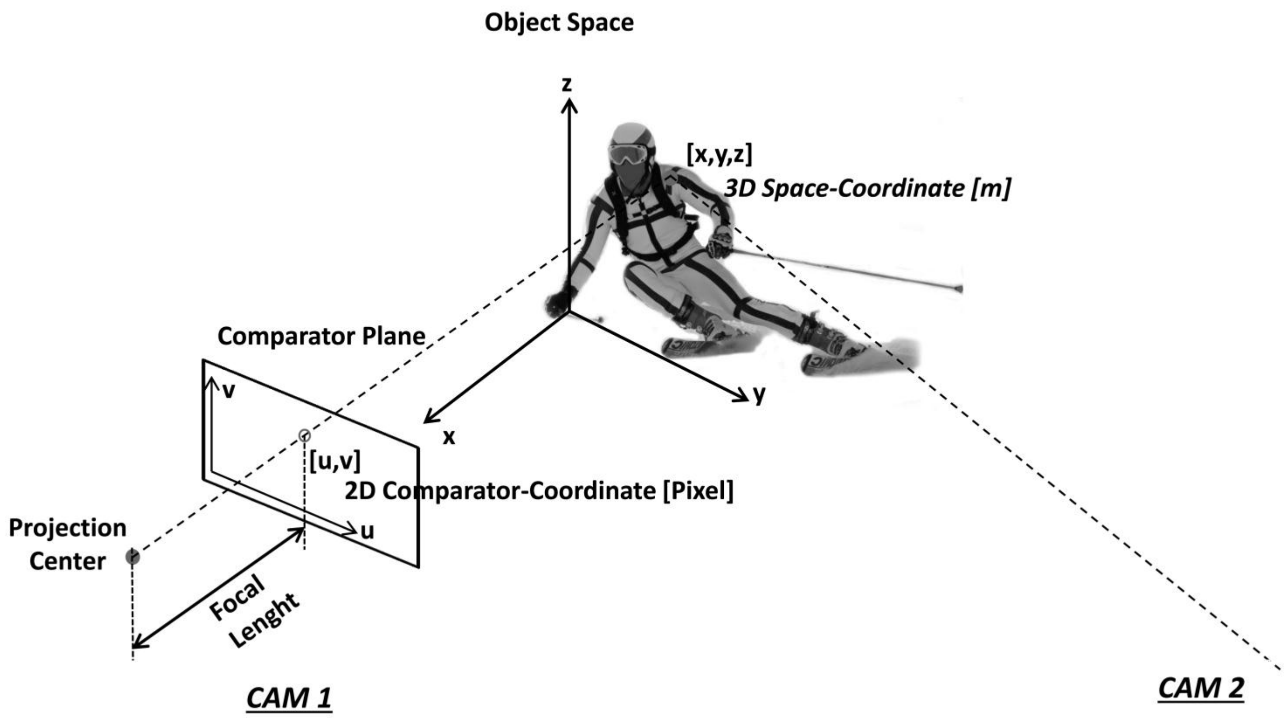


Figure 14: Direct linear transformation (DLT) method (own illustration based on Abdel-Aziz and Karara [89] and Kwon [90]; photo: P. Chevalier).

Camera Calibration

Using six or more reference points with known 3D space coordinates [x,y,x] and corresponding 2D comparator coordinates [u,v] (= 12 or more DLT-equations), the 11 unknown DLT-constants ($L_1 \ldots L_{11}$) can be resolved for each camera.

3D Reconstruction of the Segment Model

Once the DLT-constants ($L_1 \ldots L_{11}$) of all cameras are known and the cameras are calibrated. Then, the unknown 3D space coordinates [x,y,x] of the anatomical landmarks can be calculated based on the digitised points on the 2D video image [u,v] of at least two cameras (Figure 14).

DLT-Method (panned, tilted, and zoomed, non-metric cameras)

For the application of photogrammetry in sports with large capture volumes, such as alpine ski racing, the athlete must be tracked by the video cameras in order to keep him large enough in the image.[84] However, by panning, tilting and zooming, the inner and outer orientation of the camera is permanently changed.[84] As a consequence, each instant video frame has different DLT-camera constants ($L_1 \ldots L_{11}$).[84] Basically, there are three possible approaches to keep the video-cameras permanently calibrated: (1) by a "repeated" calibration of each frame using the standard DLT-Method with six or more reference points, as described above; (2) by permanently measuring the changes of the outer orientation of the camera with instrumented tripods. Based on this information, the DLT-constants of the initial calibration frame can be transformed to the DLT-constants of the actual frame; and (3) by permanently transforming the DLT-constants of the initial calibration frame to the DLT-constants of the actual frame based on the information of additional digitised reference points.

Following approach number (3), in the current thesis the plug-in software *Panning* by Drenk [85] has been used to determine the instant DLT-constants over time. The *Panning* algorithm calculates the DLT-constants of the actual image by transforming the DLT-constants of the initial camera calibration frame using additional reference points. Generally, this procedure is possible under the condition that the rotation of a camera occurs around a predefined panning or tilting axis of the tripod-head.[84] In this case, the required transformation matrix is known, if the following two presuppositions are met: (1) the positions of the panning and tilting axis are known from geodetic measurement; and (2) the change in panning angle, tilting angle and focal length has been iteratively calculated based on additional digitised reference points. In contrast to the "repeated" DLT-method where six or reference points are required for camera calibration, the *Panning* algorithm only needs two additional reference points. For the instant transformation of the DLT-constants with three unknown transformation parameters (panning, tilting, zooming), in each camera frame, at least two additional reference points (= four equations) are required in order to determine the transformation matrix and to continuously calibrate the actual image over time.

3.2.5 Post Processing and Parameter Calculation

Post-Processing

After reconstruction, the 3D position data of the anatomical landmarks was interpolated using cubic splines in the motion analysis software *Nexus (Inc. Vicon Systems)*. If the spline interpolation failed, an in *Nexus* implemented "pattern fill" algorithm was used. This algorithm fills the gaps with a trajectory similar to a marker that is part of the same rigid segment.

Thereafter, 3D position data was filtered in all three dimensions using the "optimal method with prescribed limit" implemented in *Peak Motus (Version 9, Inc. Vicon Motion Systems).* This filtering algorithm uses a zero lag Butterworth Filter (4th order) and calculates the optimal cut-off frequency for each curve and each dimension based on the analysis of the residual errors according to the Jackson Knee Method (user manual *Peak Motus, Version 9*):

1. Calculation of the average residual difference (*R*) between raw data (*X*) and filtered data (*X'*).
$$R = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X'_i)^2}{N}}$$
2. Plotting the cut-off frequency (x-axis) against the average % residual difference (y-axis).
3. Building the second derivative of the curve.
4. Finding the "knee point" of the curve (first point where a group of three second derivatives is beneath the prescribed limit of 0.1).

The aforementioned filtering algorithm has been suggested to be appropriate to filter random amplitude noise at a constant frequency, such as manual digitisation errors (user manual *Peak Motus, Version 9*). For the kinematic data of the current thesis, the optimal cut-off frequencies for all anatomical landmarks and all dimensions, calculated by Jackson Knee Method, were between 2 and 5 Hz.

Since the reconstructed kinematic data is affected by digitisation errors, the model's segment lengths may vary throughout the movement.[91] Common filter algorithms mainly smooth digitisation errors of single landmarks, while the problem with varying segment lengths remains unsolved.[91] Therefore, a segment length normalisation routine, suggested by Smith [91] and adapted by Reid [14], was additionally applied to the current data. Using the information of the real measured segment lengths of the subject and using external constraints, the endpoints of the segments were corrected by an iterative normalisation routine. For further details, please see Reid [14].

COM Calculation

The COM position was calculated based on a centre of mass model of Clauser et al. [92], adjusted with the skiing equipment. By adding the skier's equipment (helmet: 200g, ski poles: 2×250g, ski/binding: 6600g) to the athlete's body mass, a new total mass, as well as new absolute segment masses were defined. Based on this information, a new relative segment mass distribution, including the equipment, was calculated. The relative masses and the relative positions of the segment mass centres used for calculating the COM of the skier are summarised in Table 1.

Table 1: The relative masses and relative positions of the segment mass centres used for calculating COM

Segment	**Proximal Point**	**Distal Point**	**% Distance**	**% Mass**
Head (incl. Helmet)	4. Head	4. Head	100	6.2
Trunk left	7. Shoulder left	9. Hip left	44	18.5
Trunk right	6. Shoulder right	8. Hip right	44	18.5
Upper Arm left	7. Shoulder left	23. Elbow left	47	2.3
Upper Arm right	6. Shoulder right	22. Elbow right	47	2.3
Forearm left	23. Elbow left	25. Wrist left	42	1.4
Forearm right	22. Elbow right	24. Wrist right	42	1.4
Hand left (incl. Ski Pole)	27. Hand middle left	27. Hand middle left	100	0.9
Hand right (incl. Ski Pole)	26. Hand middle right	26. Hand middle right	100	0.9
Thigh left	9. Hip left	11. Knee left	44	12.0
Thigh right	8. Hip right	10. Knee right	44	12.0
Shank left	11. Knee left	13. Ankle left	42	3.8
Shank right	10. Knee right	12. Ankle right	42	3.8
Foot left	13. Ankle left	17. Binding front left	44	1.2
Foot right	12. Ankle right	16. Binding front right	44	1.2
Ski/Binding/Boot left	13. Ankle left	17. Binding front left	27.6	6.8
Ski/Binding/Boot right	12. Ankle right	16. Binding front right	27.6	6.8

Parameter Calculation

Finally parameters were calculated using the software package *MATLAB R2009b (Inc. MathWorks).* For the purposes of this thesis, several parameters characterising the skier's technique, line, energy and loading patterns have been calculated based on the 3D position data of the anatomical landmarks and the different segment vectors. The skier`s vertical movement component was calculated as the Euclidian distance (d_{vert}) between the instant ankle joint position of the outside ski and COM position, as it was suggested by Reid [14] (Figure 15).

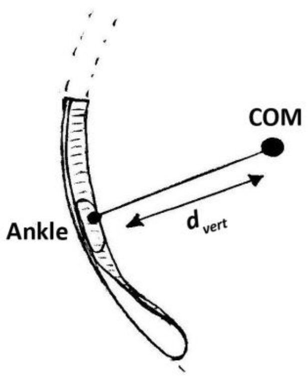


Figure 15: Parameter definition: Vertical Position (d_{vert}) (own illustration).

Based on a local coordinate system at the ankle joint, as was suggested by Schiefermüller et al. [93], the overall lateral movement component and the component in fore/aft direction were quantified by the parameters Lean Angle (λ_{Lean}) and fore/aft position ($d_{Fore/Aft}$). λ_{Lean} was calculated as the angle between the z-axis and the average left/right ankle-COM vector projected to the y-z plane (Figure 16). $d_{Fore/Aft}$ was defined to be equal to the cosine of the angle between z-axis and the outer ankle-COM vector projected to the x-z plane (Figure 16). *(Please note: in order to enable a stable calculation of the projected angle between two 3D vectors for all 4 quadrants of the Cartesian coordinate system, the advanced MATLAB function atan2 was used instead of arc tan.)*

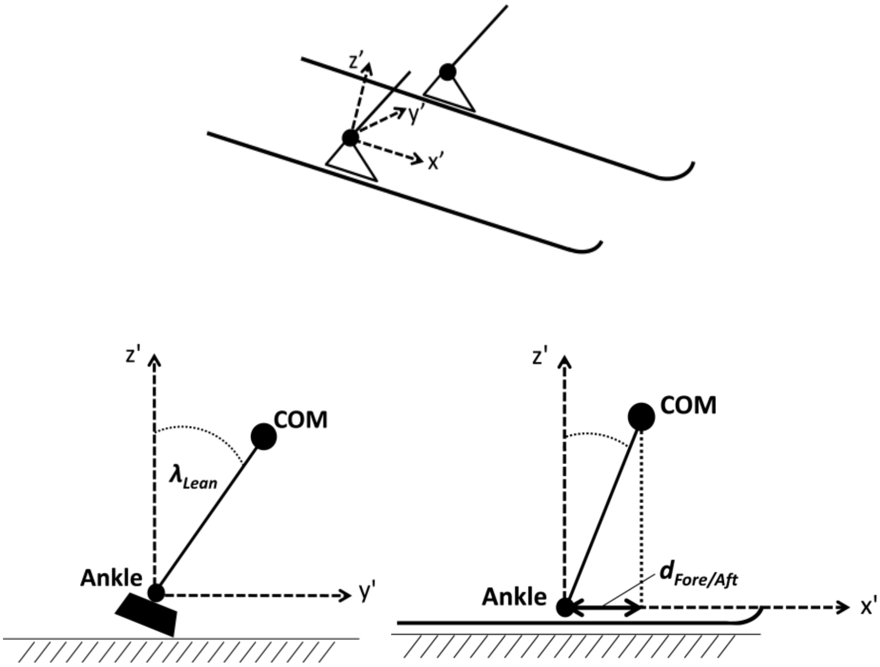


Figure 16: Parameter definition: Lean Angle (λ_{Lean}) and Fore/Aft Position ($d_{Fore/Aft}$) (own illustration).

The sum of all rotational movements was quantified as the angle between the ski axis and the direction of motion of the ankle joint, the Skid Angle (γ_{Ski}) (Figure 17). *(Please note: in order to enable a stable calculation of the projected angle between two 3D vectors for all 4 quadrants of the Cartesian coordinate system, the advanced MATLAB function atan2 was used instead of arc tan.)*

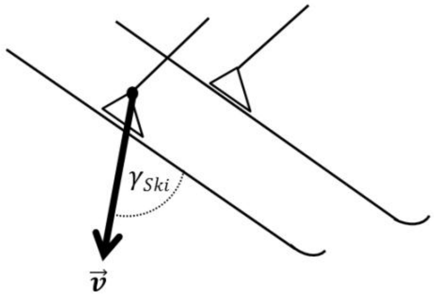


Figure 17: Parameter definition: Skid Angle (own illustration).

COM Line was characterized by the following five measures: (1) COM path length (L_{COM}), (2) COM turn radius (R_{COM}), (3) the angle between the instant direction of COM motion and the fall line, called COM traverse angle (β_{COM}) (Figure 18), and (4) the x,y position of COM at the beginning and the end of the turn. As suggested by Supej et al. [16], the beginning and the end of the turn was determined as the crossing points of the COM line projected to the slope plane and the ski line. Furthermore, based on characteristic points of ski and COM line, the turn was divided into different functional turn phases, as suggested by Reid [14], and the length distribution of the specific phases, called turn cycle structure, was used as an indicator for the timing of the skier`s technique and line within the turn.

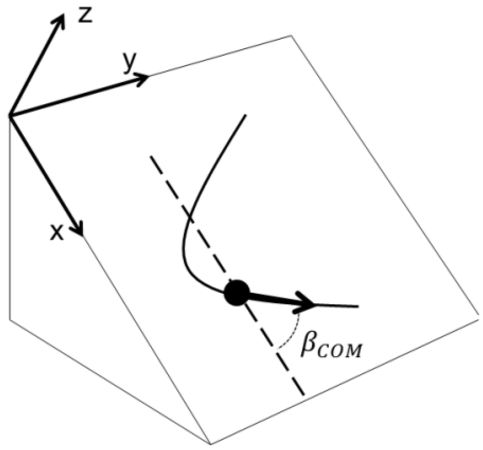


Figure 18: Parameter definition: Traverse Angle (own illustration).

Using finite central differences, the skier’s energy characteristic was quantified by the COM speed (v_{COM}) and the energy losses were calculated as the difference in mechanical energy divided by entrance velocity *($\Delta e_{mech}/v_{in}$)*:[18]

$$\Delta e_{mech}/v_{in} = \frac{\Delta E_{mech}}{m \cdot v_{in}}$$

The skier’s loading was quantified by the acting relative centripetal force (F_{cp}). F_{cp} was defined as the weight normalized centripetal force acting on COM and was calculated based on physical laws using the skier`s COM turn radius and COM speed.

3.3 Method Limitations

In various field sports such as alpine skiing, biomechanical analysis can only be performed in the normal sports’ settings and not under standardised laboratory conditions.[73] However, measuring 3D kinematics under field conditions, the controllability of the environmental conditions is limited. Moreover, as is known for all measurement systems, systematic and random instrumental errors might come into play. Hence, there are some limitations relevant to the use of video-based 3D kinematics; in particular for their application in field, which the reader of this thesis should be aware of.

3.3.1 Accuracy

Systematic Instrumental Errors (Validity)

Camera Calibration Errors

As described above, cameras are calibrated if their DLT-constants are known. In the current thesis, the cameras were permanently calibrated by transforming the DLT-constants of the initial calibration frame to the DLT-constants of the actual frame based on the information of additional digitised reference points, as suggested by Drenk [84]. Since the transformation algorithm by Drenk [85] has been proven to be highly accurate using model data,[84] the camera calibration error might be mainly depending on a systematic reconstruction error of the initial frame due to photogrammetric inaccuracy and non-linearity.[94]

The camera calibration error has been shown to be negligible in a previous study, using an experimental on-hill set-up that is highly comparable to the one of the current study.[73] Moreover, in the current study, the applied software *Panning* by Drenk [85] included an optimisation feedback tool for choosing additional reference points (poor accuracy-values highlighted those reference point constellations which were not sufficient for the transformation of the DLT-constants).

Photogrammetric Errors (Point Determination Accuracy)

The photogrammetric error is the intrinsic error of the measurement system to calculate a 3D point from different perspectives of the panned, tilted and zoomed cameras.[73] Two test measures have been suggested to describe the photogrammetric error during video-based 3D kinematic field measurements:[70, 73] (1) the comparison between geodetically measured and reconstructed static reference points along the entire area of motion; (2) the comparison of the real measured and reconstructed length of a dynamic rigid body (e.g. a ski pole).

The photogrammetric error in x-, y-, z- direction has been shown to be 11 mm, 9 mm, and 13 mm in a previous study that used an experimental on-hill set-up that is highly comparable to the one used in the current study.[73] In the same study, the resultant photogrammetric error was found to be 23 mm.[73]

Random Instrumental Errors (Reliability and Objectivity)

Intra-Experimenter Digitisation Errors

Due to the nature of manual digitising some amount of random errors might be introduced to the reconstructed 3D position data.[91] However, analysing the multiple digitisation of the same point by the same person has shown that intra-experimenter digitisation errors are less than 4 mm.[73] Moreover, for these kinds of normal-ranged digitisation errors resulting in noisy 3D point positions and varying segment lengths, filtering algorithms and iterative segment length normalization routines have shown to be highly effective.[91, 95] In addition, systematic errors in digitising can be overcome easily by systematic training sessions with the experimenter.

As a result, the current study attempted to overcome the aforementioned limitations of reliability and objectivity as follows: (1) by using a zero lag Butterworth Filter (4^{th} order) which automatically calculates the optimal cut-off frequency according to the Jackson Knee Method; (2) by applying an iterative segment length normalization routine, which corrects the segment end-points based on real measured segment lengths and external constraints;[91] and (3) by increasing the experimenters experience using the feedback of calculated segment lengths.

Inter-Experimenter Digitization Errors

In order to increase the reliability of detecting the 2D image point positions, the final passage of manual digitising was performed by one person only. Hence, inter-experimenter digitisation errors are negligible in the current study. In order to simultaneously ensure the objectivity of digitising, the experimenter passed through several digitisation training sessions using the feedback of calculated segment lengths.

Total Measurement Error

Based on the aforementioned considerations and the results of an earlier study using a highly comparable measurement method and on-hill setup,[73] the total measurement error for the reconstructed 3D positions of anatomical landmarks is expected to be less than 30 mm (photogrammetric error: ~23mm, intra-experimenter digitization error: ~4 mm).

3.3.2 Error Propagation

Generally, measurement errors are propagative and are amplified by derivation. Therefore, parameters calculated from the derivatives of 3D point position must be handled with caution when using the method of video-based 3D kinematics. In this case alternative measurement methods, which directly measure velocity (GPS/Doppler Effect) and/or acceleration (IMU) might provide even better accuracy. However, for the research purposes of the current thesis, an essential demand on the measurement method was to investigate velocity-based parameters, such as v_{COM} or $\Delta e_{mech}/v_{in}$, with respect to COM motion and to discuss them in relation with the full body movements of the skier. Therefore, the method of video-based 3D kinematics was the most valid method available for the research purposes of this thesis.

3.3.3 Capture Volume

A major limitation of video-based 3D kinematics might be that the capture volume is limited to a single- or two-gate-analysis in alpine ski racing research. On the one hand, this limits the sensitivity of the measurement method to detect tactical aspects, such as the choice of line, over longer sections or the entire course. In particular, for the sport of alpine ski racing tactical aspects play a very important role. On the other hand, to detect the small, yet substantial differences in line tactics at top level ski racing, a high degree of accuracy for COM reconstruction is indispensable. Since the second argument was of higher importance for the purposes of the current study, the use of video-based 3D kinematics can be argued to be appropriate despite this major limitation.

3.3.4 Substantial Resource Efforts

Another major limitation of the method of video-based 3D kinematics is the fact that substantial resource efforts are required for its application in field. Since both data collection and analysis are very time-consuming and require high personal and financial resources, the total amount of analysable data (subjects/trials/conditions) is strongly limited. For the field measurement building the fundament of the current thesis, for example, a total of 20 people were involved in an entire week of data collection. Furthermore, the data analysis of the 16 turns investigated for the purpose of the current thesis, took more than one year of work. Nevertheless, the complexity of analysable parameters using video-based 3D kinematics meets the complexity of alpine skiing performance and/or injury related aspects best and was, therefore, of higher importance for the current thesis.

4 Publications of the Cumulative Dissertation

This cumulative dissertation consists of the following scientific publications:

Part 1: Performance Enhancement in Alpine Ski Racing

Paper 1 (Preliminary Paper)

Spörri J, Kröll J, Schiefermüller C, Müller E. Line characteristics and performance in giant slalom. In: Müller E, Lindinger S, Stöggl T, Pfusterschmied J, editors. Book of Abstracts, 5th International Congress on Science and Skiing, St.Christoph am Arlberg (AUT). 2010: p.57.

Paper 2 (Peer-Reviewed Article)

Spörri J, Kröll J, Schwameder H, Müller E. Turn characteristics of a top world class athlete in giant slalom – a case study assessing current performance prediction concepts. *Int J Sports Sci Coach*. 2012;7(4): 647-59.

Part 2: Injury Risk Factors in Alpine Ski Racing

Paper 3 (Preliminary Paper)

Spörri J, Kröll J, Blake O, Amesberger G, Müller E. A qualitative approach to determine key injury risk factors in alpine ski racing [Research Report]: University of Salzburg; 2010. Available online at http://www.fis-ski.com/uk/medical/fis-injury-surveillance-.html (accessed 4 October 2012).

Paper 4 (Peer-Reviewed Article)

Spörri J, Kröll J, Amesberger G, Blake OM, Müller E. Perceived key injury risk factors in World Cup alpine ski racing - an explorative qualitative study with expert stakeholders. *Br J Sports Med*. 2012;46(15):1059-64. doi:10.1136/bjsports-2012-091048.

Part 3: Injury Prevention in Alpine Ski Racing

Paper 5 (Preliminary Paper)

Spörri J, Kröll J, Schiefermüller C, Müller E. The influence of course setting on kinematic and kinetic variables related to injury risk. In: Müller E, Lindinger S, Stöggl T, Pfusterschmied J, editors. Book of Abstracts, 5th International Congress on Science and Skiing, St.Christoph am Arlberg (AUT). 2010: p.108.

Paper 6 (Peer-Reviewed Article)

Spörri J, Kröll J, Schwameder H, Schiefermuller C, Müller E. Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *Br J Sports Med*. 2012;46(15):1072-77. doi:10.1136/bjsports-2012-091425.

4.1 Part 1: Performance Enhancement in Alpine Ski Racing

4.1.1 Paper 1

Preliminary Paper:

Spörri J, Kröll J, Schiefermüller C, Müller E. Line characteristics and performance in giant slalom. In: Müller E, Lindinger S, Stöggl T, Pfusterschmied J, editors. Book of Abstracts, 5th International Congress on Science and Skiing, St.Christoph am Arlberg (AUT). 2010: p.57.

LINE CHARACTERISTICS AND PERFORMANCE IN GIANT SLALOM

Jörg Spörri, Josef Kröll, Christian Schiefermüller and Erich Müller
Christian Doppler Laboratory Biomechanics in Skiing, Univ. of Salzburg, AUT

KEY WORDS: line characteristics, performance, full 3D kinematics, alpine ski racing

INTRODUCTION: While in the past the fastest turn was thought to be a purely carved turn with the smallest energy dissipation possible, nowadays tighter arcs and drifted turns can be observed in top level ski racing. These kinds of line characteristics result in higher energy dissipation during a direction change and higher velocity gains during the transition. Recent studies in slalom (Reid et al. 2007, Supej et al. 2010) mainly investigated the influence of different parameters on energy dissipation as a predictor of performance. In Giant Slalom (GS) however the distance between gates is greater and the potential for velocity gains during the transition is higher. The aim of this study was to show how a Top World Class Athlete intuitively deals with the individual and situational compromise of maximizing speed and minimizing energy losses on a typical GS section with conditions similar to world cup.

METHOD: For that purpose a full 3D kinematic field measurement, using a system of 5 panned, tilted and zoomed cameras (50 Hz) time synchronized by a gen-lock signal, was carried out. A body segment model and geodetic measured reference points were manually digitized in each frame. The 3D position data were then calculated in *PEAK MOTUS* using a Panning Algorithm. Due to the fact that this measurement method is limited by its time-consuming data evaluation, we decided to perform a case study in order to increase the trials per condition. A Top World Class Athlete performed in total 12 runs at two different course settings (26 m vertical, 10 m & 12 m horizontal). At each course setting the faster turns were compared to slower turns. For all kinematic parameters the beginning (a) and end (b) of the turn were determined by the crossing points of the center of mass (COM) line and the ski line projected to the slope plane (x,y-plane), whereas the x-axis was the direction of the fall line.

RESULTS and DISCUSSION: Trials with faster and slower sector times differed mainly in the x,y-position of the beginning and the end of the turn, as well as in the placement of the COM line in relation to the gate and the x-axis. These differences in line characteristics are also reflected in other calculated parameters, such as skid angle, edge angle, fore-aft position, turn radius, traverse angle, speed and energy dissipation. The differences in these parameters are more pronounced at the tighter course setting. There was no indication that a shorter path length is advantageous. Fast turns were initiated earlier followed by a patient "forward gliding". As soon as the necessary horizontal distance (y) has been reached ("invested"), a sharp COM direction change was performed in order to finish the turn as quickly as possible regarding the vertical distance (x). Subsequently a longer and more direct transition led to higher speed gains.

Table 1. Differences between fast and slow trials

Course	Δx_a(m)	Δx_b(m)	Δy_a(m)	Δy_b(m)	ΔL_{xyz}(m)
26/12m	-0.554	-0.547	+0.039	-0.276	+0.212
26/10m	-1.201	-0.528	+0.205	-0.213	+0.198

CONCLUSION: It is not the shortest line that results in the best performance. It is rather the timing and placement of the line, which is important for the compromise of gaining and losing speed. As methodological consequence, training of the intuitive anticipation mechanisms in terms of line / timing aspects should be a main focus for technical / tactical training.

REFERENCES

Reid R, Gilgien M, Morger T, Tjorhom H, Haugen P, Kipp R, Smith G (2010). Turn characteristics and energy dissipation in slalom. In: Science and Skiing IV, Meyer &Meyer Sport., Aachen, pp. 419-429.

Supej M, Kipp R, Holmberg HC (2010). Mechanical parameters as predictors of performance in alpine World Cup slalom racing. Scand J Med Sci Sports, pp.1-10.

4.1.2 Paper 2

***Peer-Reviewed Article*:**

Spörri J, Kröll J, Schwameder H, Müller E. Turn characteristics of a top world class athlete in giant slalom – a case study assessing current performance prediction concepts. *Int J Sports Sci Coach*. 2012;7(4): 647-59.

Turn Characteristics of a Top World Class Athlete in Giant Slalom: A Case Study Assessing Current Performance Prediction Concepts

Jörg Spörri, Josef Kröll, Hermann Schwameder and Erich Müller
Department of Sport Science and Kinesiology,
Christian Doppler Laboratory: Biomechanics in Skiing,
University of Salzburg, Austria
E-mail: joerg.spoerri@sbg.ac.at; josef.kroell@sbg.ac.at;
hermann.schwameder@sbg.ac.at; erich.mueller@sbg.ac.at

ABSTRACT
Recently, four concepts explaining time differences in alpine ski racing have been suggested. Since the demands on a "well performed" turn are contradicting among these concepts, it is unclear which turn characteristics a skier should aim for in a specific giant slalom situation. During a video-based 3D-kinematic field measurement, single repetitive runs of a world class athlete were compared regarding section times over one turn and variables explaining time differences. None of the existing concepts was able to entirely explain time differences between different performed turns. However, it was found that the skier's line and timing played an important role for time over short sections. Hence, for both science and coaching, there is a need for more comprehensive approaches that include all variables influencing performance in one concept. In coaching, one such approach could be the training of implicit adaptation mechanisms in terms of situation-dependent line and/or timing strategies.

Key words: Alpine Ski Racing, Giant Slalom, Kinematics, Section Times

INTRODUCTION

Alpine ski racing is a highly developed sport in terms of business and training concepts. However, there is still a lack of functional and biomechanical understanding of the performance relevant parameters. Only a limited number of studies have used a comprehensive biomechanical approach to investigate the influence of skier's actions and tactics on performance.[1-7] By rules, performance is defined as the shortest time from start

Reviewers: Hans-Christer Holmberg (Mid Sweden University, Sweden)
Peter Federolf (Norwegian School of Sport Sciences, Norway)

line to finish line.[8] In contrast, a high section performance can have different meanings: a short section time, a high velocity exiting the section, high velocity gain (exit velocity – entrance velocity) or low energy dissipation over the section. Since section performance also depends on the performance in the previous section,[6] in some cases, even a lower section performance may be advantageous if it results in a disproportionately higher performance in the following section.

Regarding section time as the parameter of performance, recently, four basic concepts explaining time differences have been suggested in science and/or coaching: 1) entrance velocity; 2) path length; 3) energy dissipation; and 4) the theoretical concept of the "quickest path of descent". A first explanation for shorter section times could be higher entrance velocities.[6] On the one hand, for consecutive sections, this would mean that a skier should aim for high section exit velocities in order to increase the performance of the following sections. On the other hand, there also might be a kind of "velocity barrier" above which the athlete needs to control speed to avoid mistakes,[6] which limits this strategy markedly. A second explanation could be the common coaches' doctrine that a shorter path length may result in a shorter sector time. However, a shorter path length requires shorter turn radii and may therefore lead to a loss of speed. A third explanation for shorter sector times could be found in lower mechanical energy dissipation (E_{DISS}) – calculated as the change in the skier's total mechanical energy per change in meter altitude and mass. E_{DISS} was introduced as a parameter to estimate the quality of a turn and provides information about how much energy is lost due to snow friction and air drag.[9] Consequently, the difference in total mechanical energy per mass and entrance velocity ($\Delta e_{mech}/v_{in}$) was suggested as a predictor of performance in slalom.[6] Based on this parameter, a well performed turn is a turn with the lowest energy dissipation possible in relation to entrance velocity.[6] Since high energy dissipation has been associated with high turning forces, and thus with short turn radii, it was suggested that choosing a smooth round line between the gates would lead to better performance than skiing a more direct line from gate to gate.[6] A fourth explanation for short section times could be found in the theoretical concept that models the centre of mass trajectory (COM line) of the quickest descent in a ski turn. This concept suggests that the fastest line does not have the characteristics of a smooth, round track; rather, it has a shape somewhat similar to the letter Z (Z-trajectory; "short turning-pull out straight").[10-12]

Comparing these concepts, the COM line characteristics, suggested by the concept of the "shortest path length" or the theoretical concept of the "quickest path of descent", contradict the concept of minimizing energy dissipation to increase performance. Moreover, the influence of entrance velocity on section time may depend, due to aspects of the "velocity barrier", on the situation as well.[6] Therefore, it is not *a priori* clear which turn characteristics should be aimed for in a specific giant slalom situation for a high section performance.

The purposes of this case study were threefold. The first purpose was to assess the ability of the aforementioned concepts to explain time differences observed in a one-turn section in a giant slalom course. The second purpose was to compare COM line characteristics of turns with fast and slow section times and to discuss their plausibility to be advantageous. Since course setting varies from race to race in alpine ski racing, a third purpose of this study was to compare turns with fast and slow section times for two different course settings and to assess if similar line characteristics were observable.

METHOD

A top world-class athlete (world champion in giant slalom within the same year) performed a total of 12 runs on two different course settings. For the first six runs, the vertical gate distances were 26 m with an offset of 12 m. For another six runs, the offset was changed to 10 m (Fig. 1). A total of 78 reference points, geodetic measured by theodolite, were used to calibrate a capture volume corridor of approximately 52×12×2 m (Fig. 1). In this area, the skier was filmed with a system of five panned, tilted and zoomed cameras (Panasonic F15, 50Hz, 460 line resolution, time synchronized by a gen-lock signal). All runs were recorded in a manner in which the skier covered approximately two-thirds of the picture. In each frame of each camera, a segment model with 28 points on the skier, the skis and the ski poles, as well as the three best visible reference points were manually digitized. The joint centres of the segment model were defined according to de Leva [13]. The skier's 3D position data were reconstructed using the software *PEAK MOTUS* and a DLT-based *PANNING ALGORITHM* by Drenk [14]. Post processing and parameter calculation were performed in the software *MATLAB R2009b*. Collecting kinematic data on a ski track with panning, tilting and zoomed cameras, as was performed in the present study, has been shown to be reliable and comparable to the accuracy under laboratory conditions in an earlier study.[15] The current study was approved by the Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

The COM line was calculated based on the centre mass model of Clauser et al. [16], adjusted for the skiing equipment. Ski line was defined as the trajectory of the midpoint between the ankle joints, projected to the slope plane (x,y-plane). The x-axis was orientated in the direction of the highest gradient on the slope plane (fall line). Line strategies were analysed with regard to timing and placement characteristics of the turn in relation to the gate. For parameter calculation, five characteristic points in COM / ski lines were defined (Fig. 1). The beginning *(a)* and end *(e)* of the turn were determined by the crossing points of the COM line and the ski line projected to the slope plane (x,y-plane), as proposed by Supej et al.[17] The point where COM begins to substantially change its direction (COM turn radius ≤ 30 m) *(b)*, the point of the COM passing the gate *(c)*, and the point where COM stops substantially changing its direction (COM turn radius ≤ 30 m) *(d)* were defined similarly to the definitions of Reid et al.[5] Based on these points, three turn phases were defined (Fig. 1): *Initiation (a→b)*, *COM Direction Change (b→d)*, and *Completion (d→e)*. Moreover, the turn was divided into two sections (Fig. 1): *Pre Gate Section (a→c)* and *Post Gate Section (c→e)*. The turn cycle structure was calculated as the percentage of each turn phase or turn section in relation to the whole turn. The placement of the turn was described as the distance in x- / y-direction from the position of the beginning of the turn to the gate (Δx_a / Δy_a), and the distance in x- /- y direction from the end of the turn to the gate (Δx_e / Δy_e) on the slope plane (Fig. 3).

COM path length (L_{COM}), COM turn radius (R_{COM}), and COM speed (v) were calculated numerically based on the COM-line using the four- and five-point finite central formulae.[18] Total mechanical energy (E_{mech}) was calculated as the sum of kinetic energy and potential energy. The change in specific mechanical energy per entrance velocity ($\Delta e_{mech}/v_{in}$), as a measure for energy dissipation, was calculated according to Supej et al. [6] using finite central differences, eqn (I):

$$\Delta e_{mech}/v_{in} = \frac{\Delta E_{mech}}{m \cdot v_{in}} \tag{I}$$

COM traverse angle (β_{COM}) was defined as the angle between the instant direction of COM motion and the fall-line (x-axis) (Fig. 2). Skid angle (γ_{Ski}), as a measure to estimate the degree of skidding, was defined as the angle between ski axis and the instant direction of motion of the ankle joint (velocity vector) of the outer leg (Fig. 2).

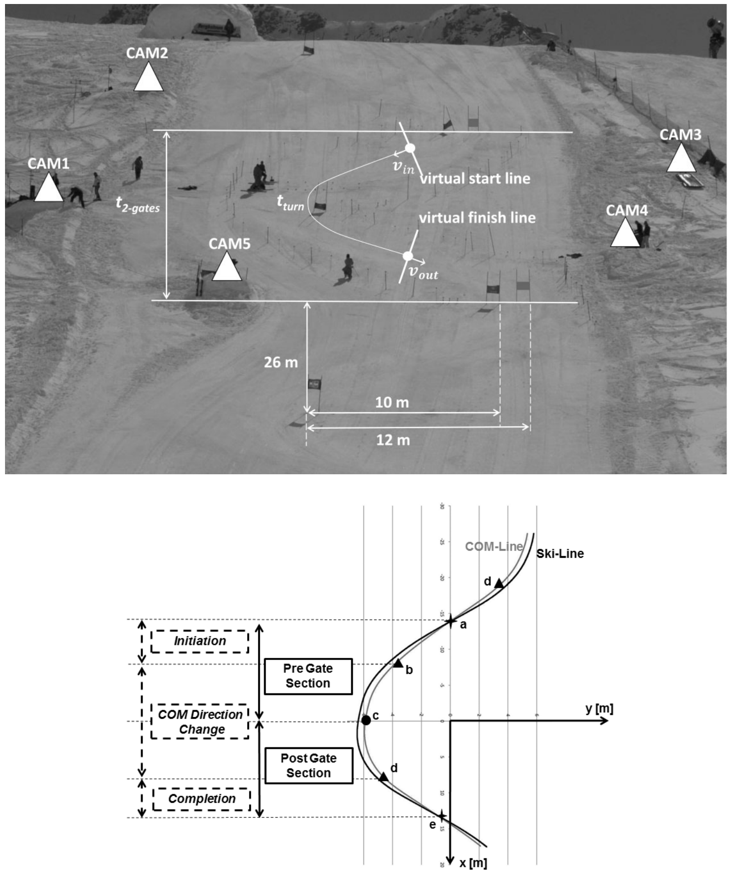


Figure 1. Overview of the Measurement Setup (top)
Characteristic Line Points and Definition of Turn Phases and Turn Sections (bottom)

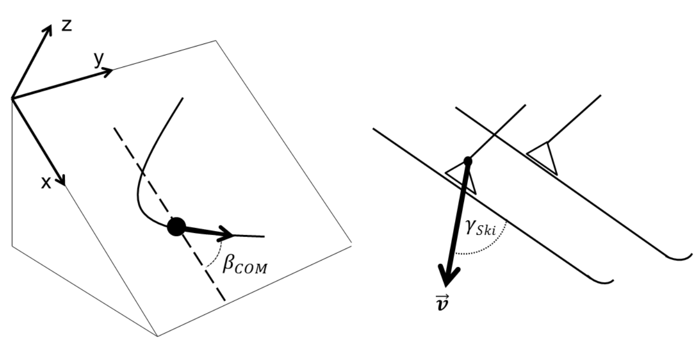


Figure 2. Angle Definitions: COM Traverse Angle (β_{COM}) (left); Skid Angle *(γ_{Ski})* (right); Velocity Vector *(v)*

Turn time was defined as the time from the beginning to the end of the turn. Since the actual positions of the starting and end points on the slope plane varied between the runs, virtual start and finish lines were constructed, as suggested by Reid [19]. Start and finish lines were defined by calculating the average COM position and the average direction of the COM velocity vector at the starting / end points of all analysed trials. Next, the lines through the average position on the slope plane and perpendicular to the average velocity vector were used as virtual start and finish lines to calculate t_{turn} (Fig. 1). Entrance speed (v_{in}) and exit speed (v_{out}) were calculated as the instant values of COM speed while passing the virtual start / finish lines (Fig. 1). Path lengths (L_{COM}), as well as the averages of the other performance related parameters (Table 1), were calculated for the section between the virtual start and finish lines. In order to ensure a constant performance over a larger than the analyzed section, times from the last gate contact before the analyzed turn until the next gate contact after the analyzed turn ($t_{2\text{-}gates}$) were determined based on high-speed video (100 Hz) captured from the opposite hillside (Fig. 1).

For assessing the ability of the current concepts to explain time differences, the turn with the fastest t_{turn} on the 26/12 m course was compared to the slowest turn (Table 1). For the comparison of COM line characteristics and turn cycle structures, the two single values of the fastest turns regarding t_{turn} (1st and 2nd ranked) were compared to the two single values of the slowest turns (5th and 6th ranked) (Table 2). The 3rd and 4th ranked turns were not considered for the analysis in order to clearly separate performance groups.

Table 1. Comparison of Turn Characteristics Between the Fastest and the Slowest Trial Regarding t_{turn} on the 26/12m Course: $^{(turn)}$ Average Start to Finish Line; $^{(pre)}$ Average Start Line to Gate; $^{(post)}$ Average Gate to Finish Line

	Fastest Trial	**Slowest Trial**
t_{turn} [s]	1.68	1.74
v_{in} [m/s]	17.58	17.29
v_{out} [m/s]	17.79	17.16
L_{COM} [m]	29.86	29.53
$\Delta e_{mech}/v_{in}^{(turn)}$ [Js/kg/m]	-3.96	-3.96
$\Delta e_{mech}/v_{in}^{(pre)}$ [Js/kg/m]	-4.51	-5.44
$\Delta e_{mech}/v_{in}^{(post)}$ [Js/kg/m]	-3.37	-2.81
$\gamma_{Ski}^{(turn)}$ [°]	12.0	12.7
$\gamma_{Ski}^{(pre)}$ [°]	17.3	24.0
$\gamma_{Ski}^{(post)}$ [°]	6.4	3.8
$R_{COM}^{(turn)}$ [m]	20.57	20.13
$R_{COM}^{(pre)}$ [m]	19.80	19.61
$R_{COM}^{(post)}$ [m]	21.20	20.45
$\beta_{COM}^{(turn)}$ [°]	21.9	22.7
$\beta_{COM}^{(pre)}$ [°]	23.1	24.3
$\beta_{COM}^{(post)}$ [°]	20.6	21.4

COM: centre of mass; t_{turn}: section time from start to finish line; v_{in}: entrance velocity at the start line; v_{out}: exit velocity at the finish line; L_{COM}: Centre of mass path length from start to finish line; $\Delta e_{mech}/v_{in}$: difference in mechanical energy divided by entrance velocity; γ_{Ski}: Skid Angle of the outside ski; R_{COM}: Centre of mass turn radius; β_{COM}: Centre of mass traverse angle.

Since using time to define performance over short sections is limited by the performance of the previous section and, therefore, by the entrance velocity,[6] a correlation analysis was performed. In order to critically discuss t_{turn} as a parameter for performance definition in the current study, Spearman's rank correlation between t_{turn} and $t_{2\text{-}gates}$, t_{turn} and v_{in}, and v_{in} and v_{out}-v_{in} was calculated. A *p*-value of 0.05 was chosen as the level of statistical significance.

RESULTS

COMPARISON OF THE FASTEST VS. SLOWEST TURN ON THE 26/12 m COURSE REGARDING PARAMETERS EXPLAINING TIME DIFFERENCES

The parameters explaining the differences in section time between the fastest and the slowest trial on the 26/12 m course are presented in Table 1. The fastest and the slowest trial on the 26/12 m course differed 3.6% in t_{turn}. L_{COM} from the start to the finish line was 1.1% longer for the fastest trial. Entrance velocity (v_{in}) was 1.7% higher, and exit velocity (v_{out}) was 3.7% higher for the fastest trial. The change in velocity from entrance to exit was +0.21 m/s for the fastest and -0.13 m/s for the slowest trial. For $\Delta e_{mech}/v_{in}$, the turn average (start to finish line) was the same for both trials, whereas there was a 20.6% lower value for the pre gate average and a 16.6% higher value for the post gate average in the fastest trial. A similar trend regarding turn sections was found for γ_{Ski}, although in total, there was a 5.8% lower turn average (start to finish line) in the fastest trial. R_{COM} was larger and β_{COM} was smaller throughout the turn in the fastest trial. The largest differences between the fastest and the slowest trial regarding performance relevant parameters were found in the pre gate average and post gate average for $\Delta e_{mech}/v_{in}$ *and* γ_{Ski}, whereas in turn average (start to finish line), similar values for these parameters were observed.

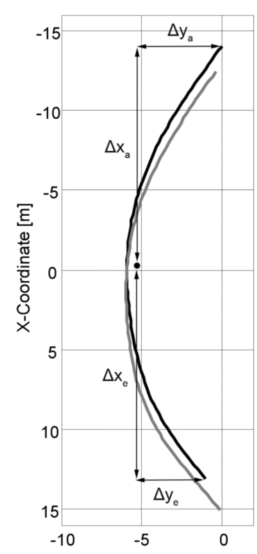


Figure 3. a) Comparison of COM Lines Between the Fastest and Slowest Trial Over One Turn Cycle at the 26/12m Course Setting (black: fastest, grey slowest)

COMPARISON OF THE FASTEST VS. SLOWEST TRIAL ON THE 26/12 m COURSE REGARDING COM LINE CHARACTERISTICS AND TURN CYCLE STRUCTURE

Comparing the COM line characteristics on the 26/12 m course, the fastest turn was initiated 1.60 m and terminated 1.98 m higher on the slope plane regarding the distance to the gate in x-direction (Δx_a / Δx_e) than the slowest turn (Fig. 3). Δy_a was 0.39 m greater and Δy_e was 0.94 m smaller in the fastest turn (Fig. 3). The fastest turn had a 2.5% longer *Initiation*, a 1.2% longer *COM Direction Change*, a 3.7% shorter *Completion* and an 8% longer *Pre Gate Section* (Fig. 4).

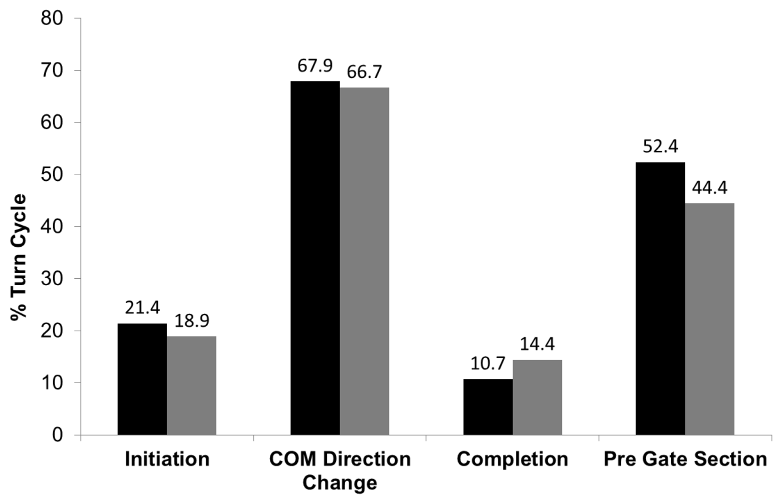


Figure 4. Comparison of Turn Cycle Structures Between the Fastest and the Slowest Trial at the 26/12m Course Setting (black: fastest, grey slowest)
For turn phase / section definition, see Figure 1.

COMPARISON OF FAST VS. SLOW TRIALS FOR TWO DIFFERENT COURSE SETTINGS REGARDING COM LINE CHARACTERISTICS AND TURN CYCLE STRUCTURE

COM line characteristics and turn cycle structure of the two fastest and the two slowest trials for two different course settings are presented in Table 2. Fast trials (1st and 2nd regarding t_{turn}) differed from slow trials (5th and 6th regarding t_{turn}) by not less than 0.04 s for the 26/12 m course and not less than 0.02 s for the 26/10 m course. This is a 2.3% difference for the 26/12 m course, and a 1.2 % difference for the 26/10 m course.

Regarding x-direction, fast turns were initiated farther from the gate and were terminated nearer the gate at both course settings. The differences of Δx_a between single values of fast and slow trials were not less than 0.45 m for the 26/12 m course, and not less than 1.13 m for the 26/10 m course. The differences of Δx_e between the single values of fast and slow trials were not less than 0.30 m for the 26/12 m course, and not less than 0.05 m for the 26/10 m course. Regarding the distance in y-direction (Δy_a, Δy_e) for both course settings, fast turns were initiated farther from the gate and terminated closer to the gate than slower turns. The differences of Δy_a between the single values of fast and slow trials were not less than 0.06 m

Table 2. Comparison of Fast vs. Slow Trials for Two Different Course Settings Regarding COM Line Characteristics and Turn Cycle Structure

	26/12 m course		**26/10 m course**	
	Fast Trials (1^{st} / 2^{nd})	**Slow Trials (5^{th} / 6^{th})**	**Fast Trials (1^{st} / 2^{nd})**	**Slow Trials (5^{th} / 6^{th})**
t_{turn} [s]	1.68	1.72	1.68	1.70
	1.68	1.74	1.68	1.70
Δx_a [m]	-14.06	-13.39	-14.34	-13.21
	-13.84	-12.46	-14.95	-13.21
Δx_e [m]	13.00	13.31	12.32	12.86
	13.01	14.98	12.36	12.41
Δy_a [m]	5.66	5.51	5.19	4.80
	5.57	5.27	5.00	4.64
Δy_e [m]	4.63	5.14	4.58	4.57
	4.70	5.57	4.40	4.74
Initiation [%]	21.4	20.9	24.1	22.2
	22.6	18.9	25.3	22.2
COM Direction Change [%]	67.9	61.6	57.8	60.5
	61.9	66.7	56.6	60.5
Pre Gate Section [%]	52.4	48.8	53.0	49.4
	50.0	44.4	54.2	50.6
Completion [%]	10.7	17.4	18.1	17.3
	15.5	14.4	18.1	17.3

COM: centre of mass; 1^{st}: first ranked trial; 2^{nd}: second ranked trial; 5^{th}: fifth ranked trial; 6^{th}: sixth ranked trial; t_{turn}: section time from start to finish line; Δx_a: position on the slope plane in x-direction at the beginning of the turn; Δx_e: position on the slope plane in x-direction at the end of the turn, Δy_a: position on the slope plane in y-direction at the beginning of the turn; Δy_e: position on the slope plane in y-direction at the end of the turn.

for the 26/12 m course, and not less than 0.20 m for the 26/10 m course. The differences of Δy_e between the single values of fast and slow trials were not less than 0.44 m for the 26/12 m course. At the 26/10 m course the performance groups overlapped slightly.

Fast turns showed a longer *Initiation* for both course settings, whereas the percentage values were higher and the differences to slow turns were greater on the 26/10 m course. Regarding *Initiation*, the differences between the single values of fast and slow trials were not less than 0.5% for the 26/12 m course and 1.9% for the 26/10 m course. Single values of *COM Direction Change* were not less than 2.7% smaller in fast trials on the 26/10 m course, while there were no clear differences between the single values of fast and slow trials found for the 26/12m course. *Pre Gate Section* was longer for fast turns at both course settings: the differences between the single values of fast and slow trials were not less than 1.2% for the 26/12m course, and not less than 2.4% for the 26/10m course. Regarding *Completion*, the differences between fast and slow trials for the 26/10 m course were not less than 0.8%, while there were no clear group differences observed at the 26/12 m.

RELATIONSHIPS AMONG PARAMETERS DEFINING PERFORMANCE

The relationships among parameters defining performance are presented in Table 3. For both course settings a positive relationship between t_{turn} and $t_{2\text{-}gates}$ was found. While t_{turn} was explainable by v_{in} only to 1.5% (r^2 = 0.015) on the 26/12 m course, there was a negative relationship between t_{turn} and v_{in} on the 26/10 m course. Between v_{in} and v_{out}-v_{in}, a negative relationship was found for both course settings.

Table 3. Spearman's Rank Correlation Coefficients for the Parameters Defining Performance

	26/12 m course				**26/10 m course**		
	$t_{2\text{-}gates}$	v_{in}	v_{out}-v_{in}		$t_{2\text{-}gates}$	v_{in}	v_{out}-v_{in}
tturn	0.984**	-0.123		tturn	0.894*	-0.828*	-
vin			-0.771	vin	-	-	-1.000**

*p<0.05; **p<0.01; ***p<0,001; t_{turn}: section time from start to finish line; $t_{2\text{-}gates}$: times from the last gate contact before the analyzed turn until the next gate contact after the analyzed turn; v_{in}: entrance velocity at the start line; v_{out}: exit velocity at the finish line.

DISCUSSION

The main findings were: 1) none of the four current performance prediction concepts was able to give a singular explanation for the difference in section time between the fastest and the slowest turn; 2) differences were found in COM line characteristics and turn cycle structures between trials with fast and slow section times; 3) similar COM line characteristic and turn cycle structure differences were found between trials with fast and slow section times for two different course settings representing both extremes of the course setting spectrum.

COMPARISON OF THE FASTEST VS. SLOWEST TURN ON THE 26/12 m COURSE REGARDING PARAMETERS EXPLAINING TIME DIFFERENCES

Performance Difference

In the current study, a difference of 3.6% in t_{turn} between the fastest and the slowest trial was found within the same athlete (Table 1). Time differences for short sections between different athletes in World Cup competitions were reported to vary by 10%.[20] Knowing that over an entire race course, differences of hundredths of a second often determine who wins a race the potential that improvements in sector time might affect the outcome of a race is quite high.

Explanation 1: Entrance Velocity

In the example of the fastest and the slowest turn on the 26/12m course, v_{in} was slightly higher for the fastest trial (Table 1); thus, it could have been influencing performance. However, it is not the sole determinant in our example. Even if entrance velocity (v_{in}) had been maintained over the whole path length of the turn (L_{COM}), it only would explain 0.01s of the 0.06 s difference in t_{turn}.

Explanation 2: Path Length

A shorter path length does not serve as an explanation for the differences in section time between the fastest and the slowest trial on the 26/12 m course (Table 1). One reason for this finding could be that the advantages of a shorter COM line do not compensate for the costs concerning energy losses due to snow friction while following this track. Another reason could be that a direct line at one gate may result in a longer line at the next gate. Hence, the costs of a more direct line would be paid at the next gate; therefore, this strategy is intuitively avoided by the athlete. This argument is in line with the findings of Lešnik and Zv̌an [3].

Explanation 3: Energy Dissipation

Comparing the fastest and slowest turn on the 26/12 m course, there is no difference regarding $\Delta e_{mech}/v_{in}$ turn average, while t_{turn} differs 3.6% (Table 1.) Surprisingly, it is possible to reach a higher performance despite the same energy dissipation throughout the turn. This indicates that $\Delta e_{mech}/v_{in}$ alone cannot predict performance in every case. A first reason for the observed phenomenon could be that even fast skiers will need to dissipate excess kinetic energy at certain time points.[5] There might be a kind of "velocity barrier" above which the athlete needs to control speed to avoid mistakes.[6] A second reason could be that this concept, due to its simplifications, is only applicable for larger differences such as technical mistakes or differences between athletes,[6] but is not sensitive for smaller differences, like different strategies used by one athlete. A third reason could be found in the distribution of energy dissipation over the turn sections. At the fastest trial, $\Delta e_{mech}/v_{in}$ was lower in the pre gate section, and higher in the post gate section (Table 1). A similar distribution for the turn sections was found for γ_{Ski} (Table 1). For a short section time, less energy dissipation / drifting and, therefore, higher velocity at the beginning of the turn may be more advantageous, since this high velocity is acting over a longer part of the turn.

Explanation 4: "Path of the Quickest Descent"

The concept of the "path of the quickest descent" [10-12] illustrates, similar to the "brachistochrone problem" in physics, that the question of when and how much potential energy is transformed into kinetic energy within a certain part of the turn, is one key for time optimization. Under the assumption of neglecting energy dissipation due to snow friction, the driving component of gravitational force and, therefore, the transformation of potential energy into kinetic energy, mainly depends on the traverse angle [21]: the smaller the angle, the closer the direction of motion to the fall line and, therefore, the higher the transfer rate of potential energy into kinetic energy. Comparing the fastest and the slowest trial at the 26/12m course, β_{COM} is smaller throughout the turn (Table 1). This implies that the acceleration due to gravity is higher over the whole turn for the fastest trial and can be explained by the line characteristic of turning less out of the direction (Fig. 3). However, R_{COM} was constantly larger throughout the turn at the fastest trial. This does not indicate a more pronounced strategy of a Z-trajectory ("short turning - pull out straight"), which was suggested to be the fastest line.[10-12] One explanation for this finding could be that this concept neglects snow friction; therefore, it is only partly applicable for skiing in reality.

Summary

This example shows the limitations of the existing concepts of performance enhancement to explain performance differences in section times. In order to give effective advice regarding performance enhancement, they would have to be balanced among each other. Therefore, there is an evident need for improvement of the existing concepts by combining them into one comprehensive concept explaining performance differences.

COMPARISON OF FAST VS. SLOW TRIALS REGARDING COM LINE CHARACTERISTICS AND TURN CYCLE STRUCTURE

Comparing the fastest and the slowest trial at the 26/12 m course turns differed in the placement of the COM line in relation to the gate and the timing within the turn cycle. The fastest turn was initiated and terminated higher regarding the vertical position on the slope plane and was turning less out of the direction of the fall line at the end of the turn (Fig. 3). Consequently, a higher percentage of the turn was executed before passing the gate in the fastest turn, and the *Initiation* was prolonged while the *Completion* was shorter (Fig. 4). Similar COM line and turn cycle differences were observed for other trials and both course settings (Table 2).

These findings are in line with the observations of Nachbauer [1], who found that a high initiation and a high termination of the turn are related to a reduction of time. In contrast to Nachbauer [1], the findings of this study indicate that a longer, not a shorter, initiation phase resulted in the best performance. This may be explained either by the different definition of the turn phases (kinetic vs. kinematic criteria), or the fact that due to the present day side cut of the ski, there are more possibilities to adapt timing by sharper turns after an elongated initiation. The observed differences in COM line characteristics and turn cycle structure seem likely to be related to short section time. As demonstrated on the example of the fastest and the slowest trial on the 26/12 m course, a higher initiation and termination of the turn needs less drifting (Δ_{Ski}) and provokes less energy dissipation ($\Delta e_{mech}/v_{in}$) prior to the gate (Table 1).

METHODOLOGICAL CONSIDERATIONS

Single-Subject Analysis

One limitation of the current study might be that only one subject was used. This limits the possibilities of generalising the study findings. However, there are two reasons why a single-subject-design may be a reasonable alternative approach to a group-design for the current research question. First, it is known that, due to differences in athletes' strengths, technical abilities or tactical reasons, different individual strategies can lead to the same performance. In this case it is problematic to conclude "the average" of different athletes (group performance) to be the best strategy for every individual.[22] Second, especially in high performance sports, effective learning strategies are mainly focused on individuals.[23]

Single-Gate-Analysis

Another limitation of the current study might be that a single-gate-analysis neglects tactical aspects regarding the choice of line down a course. Depending on the course setting before and after the analyzed section, there might be different demands on a well performed turn than a short section time. However, to detect the small, yet substantial differences at top level ski racing, a high degree of accuracy is needed, and the use of video-based 3D kinematics, is indispensable.[15, 24] This limits the capture volume to 1 giant slalom turn.

Performance Definition

A third limitation of the current study might be to define section time as a performance measure for short sections. This measure is influenced by the performance in the previous section and has the following drawbacks:[6] 1) section time is influenced by the skier's initial velocity, position and orientation; 2) a mistake close to the end has only a small impact on the analyzed section; and 3) high exit velocity, as well as the skier's position and orientation at the end of the turn has marginal influence on the analyzed section, but may be important for the following section.

In the current study there was for both course settings a strong positive relationship between t_{turn} and $t_{2\text{-}gates}$ and negative relationship between t_{turn} and v_{in} on the 26/10 m course (Table 3). Therefore, it is plausible that the performance of the skier was relatively constant over a wide section and there might be only a marginal influence of entrance velocity on section time on the 26/12 m course. In contrast, on the 26/10 m course which is turning less out of the direction of the fall line, there might be a more substantial influence.

An alternative would have been to use a section performance measure which is normalized with v_{in} instead of section time, as it was recently suggested.[6] However, in the current study, there was a negative correlation between v_{in} and v_{out}-v_{in} for both course settings (Table 3). This means that trials with low entrance velocity are gaining disproportionately more velocity throughout the turn. Therefore, it is questionable whether normalization with entrance velocity would have been an improvement for the problem of performance definition over short sections in our study.

CONCLUSION

This article illustrates the challenge for both scientists and coaches to understand the very complex relationship between parameters underlying performance in alpine ski racing. One reason for this problem might be the fact that the definition of a well performed turn may have different meanings depending on the skiing situation. Another reason might be that the current performance prediction concepts address only one aspect of a very complex relationship. In the specific case studied here, the line and/or timing aspects were critical for decreasing the turn time. Future scientific work and coaching should aim for more comprehensive approaches which consider all variables influencing performance in one concept. In science, looking at instantaneous performance rather than at section performance, as recently suggested by Federolf [25], may open new possibilities of combining different variables related to performance at the same time. In coaching, the training of the implicit adaptation mechanisms in terms of situation depending line and/or timing strategies may be an alternative approach to address different variables influencing performance at the same time.

REFERENCES

1. Nachbauer, W., Fahrlinie in Torlauf und Riesentorlauf, *Leistungssport,* 1987, 6, 17-21.
2. Pozzo, R., Canclini, A., Cotelli, C. and Baroni, G., 3D-Kinematics and Kinetic Analysis of G-Slalom in Elite Skiers at Val Badia World Cup Race in 2002, in: Müller, E., Bacharach, D., Klika, R., Lindinger, S., Schwameder, H., eds., *Science and Skiing III*, Meyer & Meyer Sport (UK) Ltd., Oxford, 2004, 125-135.
3. Lešnik, B., Žvan, M., The Best Slalom Competitors - Kinematic Analysis of Tracks and Velocities, *Kinesiology,* 2007, 39(1), 40-48.
4. Federolf, P., Scheiber, P., Rauscher, E., Schwameder, H., Luthi, A., Rhyner, H.U. and Müller, E., Impact of Skier Actions on the Gliding Times in Alpine Skiing, *Scandinavian Journal of Medicine and Science in Sports,* 2008, 18(6), 790-797.
5. Reid, R., Gilgien, M., Morger, T., Tjorhom, H., Haugen, P., Kipp, R. and Smith, G., Turn Characteristics and Energy Dissipation in Slalom, in Müller, E., Lindinger, S., Stöggl, T., eds., *Science and Skiing IV*, Meyer & Meyer Sport (UK) Ltd., Maidenhead, 2009, 419-429.
6. Supej, M., Kipp, R. and Holmberg, H.C., Mechanical Parameters as Predictors of Performance in Alpine World Cup Slalom Racing, *Scandinavian Journal of Medicine and Science in Sports,* 2010.
7. Federolf, P., Reid, R., Gilgien, M., Haugen, P. and Smith, G., The Application of Principal Component Analysis to Quantify Technique in Sports, *Scandinavian Journal of Medicine and Science in Sports,* In Press.
8. International Ski Federation (FIS), FIS International Ski Competition Rules ICR 2011, Retrieved July 16, 2012, from *http://www.fis-ski.com/data/document/icr-2011july_web.pdf*
9. Supej, M., Differential Specific Mechanical Energy as a Quality Parameter in Racing Alpine Skiing, *Journal of Applied Biomechanics,* 2008, 24(2), 121-129.
10. Lind, D., Sanders, S.P., *The Physics of Skiing: Skiing at the Triple Point*, Springer Verlag, New York, 2004.
11. Hirano, Y., Quickest Descent Line During Alpine Ski Racing, *Sports Engineering,* 2006, 9, 221-228.
12. Reinisch, G., A Physical Theory of Alpine Ski Racing, *Spectrum der Sportwissenschaften,* 1991, 3(1), 26-50.

13. de Leva, P., Joint Center Longitudinal Positions Computed from a Selected Subset of Chandler's Data, *Journal of Biomechanics,* 1996, 29(9), 1231-1233.

14. Drenk, V., Bildmeßverfahren für Schwenk: Und Neigbare Sowie in der Brennweite Variierbare Kameras, *Schriftenreihe zur Angewandten Trainingswissenschaft 1*, Institut für Angewandte Trainingswissenschaft, 1994, 130-142.

15. Klous, M., Müller, E. and Schwameder, H., Collecting Kinematic Data on a Ski/Snowboard Track with Panning, Tilting, and Zooming Cameras: Is There Sufficient Accuracy for a Biomechanical Analysis?, *Journal of Sports Sciences,* 2010, 28(12), 1345-53.

16. Clauser, C.E., Mc Conville, J.T., Young, J.W., Weight, Volume and Centre of Mass Segments of the Human Body. *AMRL TR-69-70*, Wright-Patterson Air Force Base, OH, 1969.

17. Supej, M., Kugovnic, O., Nemec, B., Kinematic Determination of the Beginning of a Ski Turn, *Kinesiologia Slovenica,* 2003, 9, 11-17.

18. Gilat, A., Subramaniam, V., *Numerical Methods for Engineers and Scientists*, John Wiley & Sons, Inc., Hobocken, NJ, 2008.

19. Reid, R., *A Kinematic and Kinetic Study of Alpine Skiing Technique in Slalom*, Ph.D. Thesis, Norwegian School of Sport Sciences Oslo, 2010.

20. Supej, M. and Cernigoj, M., Relations Between Different Technical and Tactical Approaches and Overall Time at Men's World Cup Giant Slalom Races, *Kinesiologia Slovenica,* 2006, 12, 63-69.

21. Jentschura, U.D. and Fahrbach, F., Physics of Skiing: The Ideal-Carving Equation and its Applications, *Canadian Journal of Physiology,* 2004, 82(4), 249-261.

22. Bates, B.T., Single-Subject Methodology: An Alternative Approach, *Medicine and Science in Sports and Exercise,* 1996, 28(5), 631-8.

23. Schöllhorn, W.I., Müller, E., Lindinger, S., Raschner, C., Schwameder, H. and Benko, U., Individuality and Generality in Ski Turn Techniques, in: Müller, E., Schwameder, H., Raschner, C., Lindinger, S. and Kornexl, E., eds., *Science and Skiing II*, Verlag Dr. Kova_ Hamburg, 2001.

24. Schiefermüller, C., Lindinger, S. and Müller, E., The Skier's Centre of Gravity as a Reference Point in Movement Analyses for Different Designated Systems, in: Müller, E., Bacharach, D., Klika, R., Lindinger, S. and Schwameder, H., eds., *Science and Skiing III*, Meyer & Meyer Sport (UK), Ltd., Oxford, 2005, 172-185.

25. Federolf, P.A., Quantifying Instantaneous Performance in Alpine Ski Racing, *Journal of Sports Sciences,* 2012, 30(10), 1063-8.

4.2 Part 2: Injury Risk Factors in Alpine Ski Racing

4.2.1 Paper 3

Preliminary Paper:

Spörri J, Kröll J, Blake O, Amesberger G, Müller E. A qualitative approach to determine key injury risk factors in alpine ski racing [Research Report]: University of Salzburg; 2010. Available online at http://www.fis-ski.com/uk/medical/fis-injury-surveillance-.html (accessed 4 October 2012).

This article can be retrieved from:

http://www.fis-ski.com/uk/medical/fis-injury-surveillance-.html

4.2.2 Paper 4

Peer-Reviewed Article:

Spörri J, Kröll J, Amesberger G, Blake OM, Müller E. Perceived key injury risk factors in World Cup alpine ski racing - an explorative qualitative study with expert stakeholders. *Br J Sports Med*. 2012;46(15):1059-64. doi:10.1136/bjsports-2012-091048.

OPEN ACCESS

Perceived key injury risk factors in World Cup alpine ski racing—an explorative qualitative study with expert stakeholders

Jörg Spörri,[1] Josef Kröll,[1] Günter Amesberger,[1] Ollie M Blake,[2] Erich Müller[1]

[1]Department of Sport Science and Kinesiology, University of Salzburg, Hallein-Rif, Austria
[2]Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, Canada

Correspondence to
Jörg Spörri,
Department of Sport Science and Kinesiology, University of Salzburg, Schlossallee 49, 5400 Hallein-Rif, Austria;
joerg.spoerri@sbg.ac.at

Received 9 February 2012
Accepted 4 July 2012
Published Online First
9 August 2012

ABSTRACT

Background There is limited knowledge about key injury risk factors in alpine ski racing, particularly for World Cup (WC) athletes.

Objective This study was undertaken to compile and explore perceived intrinsic and extrinsic risk factors for severe injuries in WC alpine ski racing.

Methods Qualitative study. Interviews were conducted with 61 expert stakeholders of the WC ski racing community. Experts' statements were collected, paraphrased and loaded into a database with inductively derived risk factor categories (Risk Factor Analysis). At the end of the interviews, experts were asked to name those risk factors they believed to have a high potential impact on injury risk and to rank them according to their priority of impact (Risk Factor Rating).

Results In total, 32 perceived risk factors categories were derived from the interviews within the basic categories Athlete, Course, Equipment and Snow. Regarding their perceived impact on injury risk, the experts' top five categories were: system ski, binding, plate and boot; changing snow conditions; physical aspects of the athletes; speed and course setting aspects and speed in general.

Conclusions Severe injuries in WC alpine ski racing can have various causes. This study compiled a list of perceived intrinsic and extrinsic risk factors and explored those factors with the highest believed impact on injury risk. Hence, by using more detailed hypotheses derived from this explorative study, further studies should verify the plausibility of these factors as true risk factors for severe injuries in WC alpine ski racing.

INTRODUCTION

World Cup (WC) alpine ski racing is known as a high-risk sport.[1–3] Injury rates over the WC seasons 2006/2007 and 2007/2008 were found to be 36.7 per 100 athletes, which was alarmingly high.[1] Slightly over 30% of all recorded injuries were severe (>28 days of absence).[1] Severe injuries may hinder the athlete from returning to the sport and they also may increase the risk of reinjury.[4] Moreover, long-term adverse health effects are possible, such as a higher prevalence of early osteoarthritis.[4]

To be able to develop effective prevention strategies for these injuries, a comprehensive model for injury causation should be used.[5] Such a model should account for all the factors involved (figure 1): the intrinsic and extrinsic risk factors, as well as a precise description of the inciting event (injury situation and injury mechanism).[5 6] Regarding anterior cruciate ligament injuries, the dominant injury type in WC alpine ski racing,[1] recent studies provided a deeper understanding of the injury mechanisms.[7–9] Furthermore, the skiing situation leading to these injuries has been described based on experts' visual analyses.[10] On the basis of these analyses, athletes' technical mistakes, inappropriate tactical choices, visibility and snow conditions were suggested to be the main contributors leading up to injury situations.[10] However, the factors that make the athletes predisposed and susceptible to injuries (intrinsic and extrinsic risk factors) are rather unclear for WC alpine ski racing. These factors may be completely different than the risk factors for recreational skiing.[11–14] This said, knowing the factors that make the athletes predisposed and susceptible to injuries is essential for their prevention.[5 6]

Recently, significant changes to many aspects of WC ski racing have occurred; the introduction of carving skis and water-injected slopes being two of the most prominent.[15 16] As a consequence of these changes, the course settings and the athlete's technique and physical preparation changed as well.[17–19] These numerous changes have added to the complexity of the injury problem. This makes it difficult to determine the key risk factors for severe injuries based on retrospective study designs. Moreover, prospective designs are currently limited by the lack of detailed hypotheses about potential key risk factors. Therefore, a qualitative interview approach with expert stakeholders of the WC ski racing community was chosen for this study. The aim of this explorative study is to compile a list of perceived intrinsic and extrinsic risk factors for severe injuries in alpine WC ski racing. Furthermore, it is to derive precise qualitative statements about those factors that are thought to have the highest impact on injury risk in order to provide more detailed hypotheses for further studies.

METHODS

Interview participants

The analysis involved individual interviews with representatives from different expert stakeholder groups (table 1). The participation on the study was voluntary. The sampling was chosen based on the principle of maximal variation of perspectives and was enlarged as long as new perspectives were obtained.[20] However, compared to WC coaches, WC athletes, males in particular, demonstrated lower interest for participating in the interview process. Therefore, the gender-specific perspectives were unbalanced within the expert group 'WC athletes' (female: n=7, male: n=4).

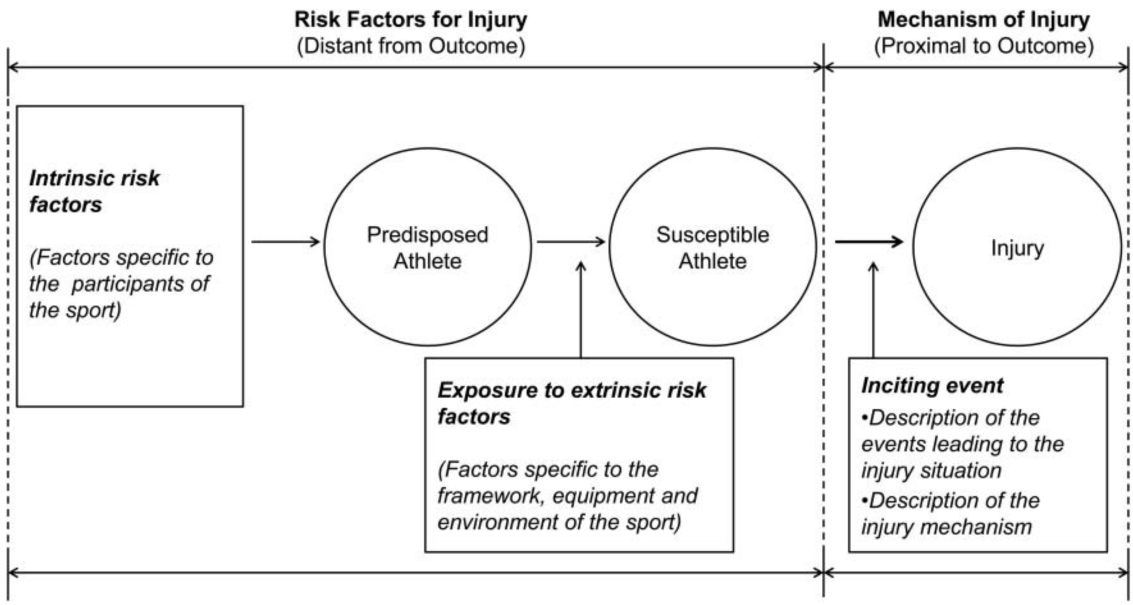


Figure 1 Model for injury causation (adapted from Meeuwisse and Bahr *et al*).[5 6]

Interview collection

The individual interviews took place in 2010, with two concentrated phases during the WC events in Kvitfjell and the WC finals in Garmisch. Each Interview lasted 40–70 min and was conducted by a native speaker in either German or English. All interviews were recorded using a digital voice recorder (Olympus VN-6800PC; Olympus Corporation, Tokyo, Japan) to ensure accuracy in analysis. The interviews were semistructured with prepared questions; however, certain areas were examined through improvisation based on the responses of the interviewee,[20–22] with each interview ultimately covering the same material. Generally, the interviews were broken down into two parts and moved from general to specific questioning (table 2).[22]

In the first part of the interview (Risk Factor Analysis—RFA), general, detailed and specific questions were posed regarding whether they saw any noticeable problems or distinct features that are related to severe injuries (>28 days of absence as defined by Fuller *et al*[23]). The general section was left open to allow the interviewee the opportunity to address any area they considered to be problematic. Circular questioning was used to draw out as many ideas from the interviewees as possible with minimal influence from the interviewer.[20] Each basic category (Equipment, Course Setting, Snow and Athlete) not mentioned by the interviewee in the general section was asked in the detailed section. For the specific section, a checklist with perceived risk factors was used by the interviewer to keep track of the topics covered. Any topic from this checklist not mentioned during previous questioning was asked in this section. This checklist with perceived risk factors was established through trial interviews with coaches, athletes and research team members, and was dynamically enhanced throughout the data collection process based on the interviews previously conducted.[20] In the second part of the interview (Risk Factor Rating—RFR), participants were asked to name and rank, out of all the perceived injury risk factors discussed in the

Table 1 Description of the interview participants

Expert group	Inclusion criteria	Perspective	n
WC athletes	Top 15 athletes' WC ranking	All disciplines ('Allrounder') (n=7) Speed disciplines only (n=3) Technical disciplines only (n=1)	n=11
WC coaches	Top 8 nations' WC ranking	Head coaches (n=8) Group coaches (n=11)	n=19
Officials/race organisers	Responsible for WC courses	FIS race directors (n=5) TD (WC organizer) (n=5) Slope engineer (n=1)	n=11
Representatives ski equipment companies	Top 5 WC ranking of ski equipment suppliers	Head engineers (n=5) Service-men (n=5)	n=10
Topic specific experts	Expert with a superior specific background	Science (n=3) Expert ski equipment (n=1) Expert safety equipment course (n=1) Expert snow preparation (n=1) Expert physical training (n=1) Expert youth ski racing (n=1) Disabled former WC athlete (n=1) Parent of severely injured WC athlete (n=1)	n=10
		Total	n=61

FIS, International Ski Federation; TD, Technical Delegated; WC, World Cup.

Table 2 Layout and questions for the interview process: part 1 moves from general to specific questions about distinct features or noticeable problems related to severe injuries in alpine ski racing; part 2 compiles and ranks key risk factors

	General questions	Considering severe injuries in alpine ski racing, from your experience and perspective can you see or do you notice any distinct features or noticeable problems?	
1	Detailed questions	In addition to the points you have mentioned, others also see problems in the basic categories of…(Equipment, Course Setting, Snow and Athlete—only asking about those areas not already mentioned). Considering this area and severe injuries in alpine ski racing, from your experience and perspective can you see or do you notice any distinct features or noticeable problems?	RFA
2	Specific questions	If we return again to the area of … (Equipment, Course Setting, Snow and Athlete)…often the points… (asking about specific aspects of each area listed in the checklist and only asking about those specific areas not already mentioned)…are mentioned	
		Considering this area and severe injuries in alpine ski racing, from your experience and perspective can you see or do you notice any distinct features or noticeable problems?	RFR
	Ratings	We have been talking about a variety of aspects relating to severe injuries in alpine ski racing. If you think about your previous statements, what do you consider the key risk factors and how would your rank them?	

RFA, risk factor analysis; RFR, risk factor rating.

interview, the factors they believed had high potential impacts on the risk of severe injuries.

Interview analysis

Risk Factor Analysis

The RFA sections of the interviews were processed with methods of qualitative research[20 21] by native speakers in either German or English. At the beginning of the process, 15 audiotaped interviews, which were randomly chosen within the expert groups, were fully transcribed word for word based on common transcription rules. Thereafter, a process of reduction was used to take the full transcripts and create concise summaries of the statements (paraphrasing).[20] The paraphrased statements, in either German or English, were then separated into basic categories, as well as three subcategory levels based on their similarities and their distinctions. Finally, the coded statements were entered into a digital database in their particular categories (named in English). Later, during the evaluation process, paraphrased statements from the remaining 46 interviews were extracted from the audio files without full transcriptions and were entered into the database. The categories of the database were dynamically enhanced during the analysis process based on the statements, as long as new perspectives were obtained.[20]

Risk Factor Rating

For the RFR section of the interview, in principal, the same data processing as for the RFA section was performed (audio file → transcription → paraphrasing) and paraphrased statements were entered into categories of the same name. For this analysis all 61 interviews were considered. In the RFR section, the interviewees were asked to select, out of all mentioned risk factors, the ones with high potential impact on injury risk, and to rank them in order of their perceived priority. All interviewees identified between one and six risk factors believed to have high impact on injury risk, whereby the majority named two or three factors. Depending on which impact on injury risk the interviewee assigned each perceived key risk factor, a ranking number was given to each statement. A lower ranking number means a higher potential impact of the risk factor, with ranking number '1' given to the highest impact. For each perceived key risk factor that was named in the RFR section, the frequency of mention and the mean of the rank numbers given by the experts were analysed. Then, a rank order for the frequency of mention and a rank order of the assigned mean rankings were created. Finally, based on the sum of these two rank orders, an overall ranking list of perceived key injury risk factors was defined.

RESULTS

RFA—derivation of inductive categories

The experts' perceived injury risk factor categories are presented in alphabetic order in table 3. Within the basic categories Athlete, Course, Equipment and Snow, a total of 32 risk factor categories were inductively derived from the qualitative analysis of the interviews.

RFR—quantitative analysis of the categories

The experts' priorities of perceived key injury risk factor categories regarding their potential impact on injury risk are presented in table 4. A total of 25 risk factors categories were suggested to play a key role for injury causation.

RFA—qualitative content analysis of the categories

Owing to space restrictions in this article, the results of the qualitative content analysis are only presented for the experts' top five key injury risk factors. An overview of the corresponding quote categories and example quotes are given in table 5.

DISCUSSION

This study was undertaken to compile and explore perceived intrinsic and extrinsic injury risk factors for severe injuries in WC alpine ski racing. The inductively derived risk factor categories were presented in table 3. This list may serve as a

Table 3 Risk Factor Analysis: perceived injury risk factor categories derived from the interviews within the basic categories Athelte, Course, Equipment and Snow (in alphabetic order)

Athlete	*Course*
Aspects of body temperature	Poor visibility
Athlete's adaptability	Course maintenance during race
Athlete's crash behaviour	Course setting in general
Athlete's individual responsibility	Jumps
Athlete's race preparation	Level of course difficulty
Fatigue	Safety net position and spill zone
Genetics and anthropometry	Speed and course setting aspects
Physical aspects	Speed and topographic aspects
Psychological aspects	Speed in general
Preinjury aspects	Topography in general
Skiing technique and tactics	
Equipment	*Snow*
Binding/plate	Aggressive snow conditions
Gates (panels and poles)	Changing snow conditions
Protectors and helmets	Smooth snow surface
Racing suits	Techniques of snow preparation
Ski	
Ski boot	
System ski, plate, binding, boot	

Table 4 Risk Factor Rating (RFR): experts' priorities of perceived key injury risk factor categories regarding their potential impact on injury risk

Perceived priority	Potential key injury risk factor	Mentions in RFR	Rank	Mean rank RFR	Rank	∑ Rank points
1	System ski, plate, binding, boot	22	1	1.73	2	3
2	Changing snow conditions	17	2	1.79	4	6
3	Speed and course setting aspects	9	6	2.00	7	13
4	Physical aspects	6	9	1.92	6	15
4	Speed in general	11	4	2.23	11	15
6	Techniques of snow preparation	9	6	2.28	12	18
7	Aggressive snow conditions	8	8	2.31	13	21
7	Fatigue	15	3	2.83	18	21
7	Skiing technique and tactics	3	16	1.83	5	21
10	Athletes' race preparation	2	20	1.75	3	23
10	Preinjury aspects	1	22	1.00	1	23
12	Bad visibility	3	16	2.00	8	24
12	Speed and topographic aspects	5	10	2.60	14	24
14	Jumps	11	4	3.45	24	28
15	Course setting in general	5	10	2.90	20	30
15	Gates (panels and poles)	5	10	2.90	20	30
17	Athletes' individual responsibility	3	16	2.67	15	31
17	Psychological aspects	1	22	2.00	9	31
17	Racing suit	3	16	2.67	15	31
20	Binding/plate	5	10	3.00	22	32
20	Level of course difficulty	1	22	2.00	10	32
22	Safety net position and spill zone	4	14	2.88	19	33
23	Ski	4	14	3.13	23	37
23	Ski boot	2	20	2.75	17	37
25	Protectors and helmets	1	22	4.50	25	47

Mentions in RFR: number of subjects which mentioned a specific factor to have superior impact on injury risk (key risk factor). Mean rank RFR: mean value of the ranks given to a specific key risk factor by the experts. A low mean rank means high priority.

guideline for further studies. Regarding their perceived impact on injury risk, the experts' top five risk factor categories were: system of ski, binding, plate and boot; changing snow conditions; speed and course setting aspects; physical aspects; and, speed in general. Owing to space restrictions in this article, only these five risk factor categories are discussed in depth. In the following synopsis, the experts' direct quotes are highlighted with quote signs and italic font.

System ski, binding, plate and boot

According to the experts' rating, the 'system of ski, binding, plate and boot' is too direct in force transmission, too aggressive in the ski–snow interaction, and too difficult to get off the edge once the ski is carving. As a result, as argued by some experts, the equipment is not controllable if the athlete loses his/her balance due to its unpredictable self-dynamic behaviour. Driving factors for these equipment handling problems may be: (1) the skis' side-cut

> "Less side-cut means less force and less violence in injury situations."

(2) the skis' width

> "Wider skis make it harder to get up on and off the edge"

(3) the skis' length

> "Longer skis are safer and you feel more comfortable at high speed runs."

(4) a homogenous bending line of the skis

> "The binding plate takes partly the responsibility for today's injury frequency, since it significantly influences the bending line of the ski and causes that the ski does a less likely break-away or slides."

(5) the skis' torsional stiffness

> "There is a possibility to make the skis more aggressive by changing the torsional stiffness"

and (6) the weight of the whole equipment system

> "…if this mass once is accelerated, it can lead to an uncontrolled self-dynamic behaviour of the equipment."

Furthermore, stiff boots and high standing heights are believed to play a central role for injuries

> "Boots are too stiff…especially at low temperatures boots get very direct regarding force transmission."

> "Standing high plays a central role, which must be reduced. Nowadays, unhealthy lever arms result in high forces which act on the body."

All suggested driving factors are plausible and are in line with the mechanical theory of skiing.[24–27] Furthermore, both high standing heights and strong side-cuts of the skis have been suggested to favour a sudden catch of the edge while skiing,[15] which is a crucial factor leading up to the injury mechanisms specific for WC alpine ski racing.[7]

Changing snow conditions

Widely discussed among the ski racing community, changing snow conditions, in particular within one run, requires great effort for the athlete to adapt immediately and it is difficult to set up and prepare the equipment for all different conditions. Generally, injected snow and icy conditions are believed to be safer than aggressive snow conditions.

 Br J Sports Med 2012;**46**:1059–1064. doi:10.1136/bjsports-2012-091048

Table 5 Qualitative content analysis: generalised quote categories and example quotes of the top five perceived injury risk factor categories derived from the interviews

Risk factor and quote categories	Example quotes
System ski, plate, binding, boot	
System is too aggressive in ski–snow interaction	"The system ski, boot, binding, plate is too aggressive and there should be more room for mistakes"
System is too direct in force transmission to the body	"It is always tried to make the force transmission more direct … but this development could go at the expense of safety"
System is difficult to control	"It happens often, that if you lose the grip on the outer ski the inner ski catches the edge and catapults you out of the turn"
System has a strong self-dynamic/self-steering behaviour	"If the equipment is once out of control, it develops a certain self-dynamic behaviour and the athlete does not get rid of the edge"
Changing snow conditions	
Changing conditions from run to run make it difficult for the athletes to adapt	"Every injected slope is different making it hard to have the proper equipment"
Changing conditions within one run make it difficult for the athletes to adapt	"A mix of injected and aggressive snow on the same slope is a problem for injury as it is hard to setup the equipment for both situations"
Changing conditions due to bib-number can be a safety problem	"Changes of the slope during the race mainly affect racers with lower levels"
Speed and course setting aspects	
Speed in combination with small turn radii is dangerous	"Speed in combination with tight turns is more dangerous than a more opened turn at high speed"
Speed in combination with small turn radii leads to higher forces	"As result of the high turn speed, there are acting high external forces"
Speed in turns is higher today than in the past	"The increase of turn speed was in the last few years disproportionately higher than the increase in athletes' strength"
Speed can be controlled through course setting	"Speed control must be done by course setting"
Speed control through course setting can be problematic	"A tighter course set does not decrease the risk, since forces are increased. Therefore, speed reduction by course setting is not wise"
Speed cannot be controlled through course setting in every case	"Speed control through tighter course setting is useless as long as the athlete is still able to carve the tighter radius"
Physical aspects	
High fitness level is important to reduce injury risk	"Physical training is very important for athletes to avoid injuries"
Athletes' fitness levels are not always sufficient	"A lot of younger athletes (women in particular) don't get enough time to work on their conditioning as they are selected at young age and have pressure to move up in the ranks"
Athletes' fitness levels are already at the limit and cannot be further improved	"The physical conditioning of the human body reaches its limit earlier than the equipment development"
Forces acting on the body are too high and must be reduced	"The forces are too high for the human body and should be reduced in reasonable degree"
Too specialised physical training is a safety problem	"Physical training usually aims on reaching with a minimal effort a maximum for the competition, so that there are reserves left"
Speed in general	
High speed increases the 'destructive potential' of the energy involved	"Crashes at high speed lead more frequently to injuries than crashes at low speed"
Constantly high speed over a long sector is a injury risk factor	"The factor speed is a huge problem, especially a constantly high speed, which deceives the senses"
Speed in general should be lowered for safety reasons	"A speed reduction of 20–30km/h would make sense"

> "Icy snow conditions are safer than aggressive snow, because the equipment does not react as fast"

Moreover, according to some experts, snow injection reduces the changes due to bib number (traces) and, therefore, may increase safety. However, partial injection is suggested to be problematic since it changes the mechanical proprieties of the snow,[16] and the equipment is set up and prepared for the iciest part. Consequently, the ski–snow interaction is too direct in force transmission when entering a section with 'grippy' artificial snow

> "If on a slope with aggressive snow only a couple of turns are injected, the setup must be tuned in a manner that allows skiing on ice…in doing so the set-up gets too aggressive in sections without ice."

Hence, the influence of the slope preparation and maintenance on the ski–snow interaction seems to be an important key for a better understanding of injuries in WC alpine ski racing.[7 10]

Speed and course setting aspects

According to the experts, in carved turns speed in combination with small turn radii leads to high forces on the body. This is theoretically plausible and coincides with the literature.[15 25] Generally, some experts feel that speed in turns has increased in the last years

> "The big difference today with the carving skis is that you do not loose so much speed through a turn making it more risky for injuries."

Typically, the reduction or control of speed in turns is attempted by course settings that turn more out of the direction of the fall line. However, according to the experts, this is not the key for risk reduction in every case. As long as the turn still can be carved and more skidding is not provoked, speed control by course setting may not be very effective; rather, higher forces may occur due to smaller turn radii at a similar speed. An alternative approach may be course settings that locally slow down the racers in a substantial manner before key sections

> "…it should be given more importance to tactical aspects, so that the athlete really has to decide where to slow down and to pass with full speed."

Physical aspects

According to the experts, a superior fitness level is one of the most important perceived factors for injury prevention

> "Physically weak athletes have a higher risk for injuries."

Even though the importance of a superior fitness level for injury prevention is widely accepted in practice, no definite conclusions can be made based on the existing literature.[28] However, fatigue is known to have a negative impact on balance control,[29] and physical fitness has an effect on reaction time during exercise.[30] Therefore, it seems to be reasonable that a lack of fitness and early fatigue could be risk factors for injuries. According to the experts, there are actually two main problems in alpine WC ski racing regarding 'physical aspects' of the athletes: (1) the fitness level of today's top athletes reaches physical limitation and cannot be further improved in order to resist the outer forces and (2) younger athletes, in particular women, are not always sufficiently prepared to enter the WC.

Speed in general

According to the experts, high skiing speed is a general perceived risk factor for injuries, in particular, if speed is constantly high. They argue that this deceives the senses and results in a loss of concentration. In addition, the athlete may have too little time to react and/or correct if an injury situation develops rapidly at high skiing speeds.[7 15] High skiing speeds mean high kinetic energy and, as a result, can induce serious injuries in the event of a quick energy conversion during injury events or crashes

> "…technical mistakes do not have as fatal consequences at lower speed."

Therefore, some experts think that speed in general should be reduced.

Methodological considerations

The qualitative approach used in this study contributes to the theoretical and conceptual body of knowledge and adds new perspectives regarding perceived injury risk factors in alpine ski racing. However, there are some dangers/limitations related to the study design used.

First, the applied study design does not allow for verification of whether the perceived injury risk factors are true risk factors. These factors primarily need to be validated against formal aetiological studies in order to confirm their status as injury risk factors.

Second, the quality of results depends on the quality of the interviews, as well as on the expertise and degree of reflection of the interviewees. Therefore, it was attempted to provide a comfortable environment in which to conduct the interviews, and each individual interview started with an open-ended question in order to encourage the interviewee to speak freely.[20] In order to maximise the richness of data, the sample was chosen in an attempt to maximise the variation of expertise and perspectives.[20] However, due to the voluntary character of this study, some limitations remain with respect to an unbalanced sampling, especially, for the quantitative analysis of the interviews.

Third, the qualitative interview approach includes the danger of subjectivity. Therefore, three different researchers were involved in conducting and analysing the interviews: (1) the first five interviews were conducted and processed by all three researchers together and (2) for all interviews, the classification of the paraphrased statements into risk factor categories was performed by all researchers together in a permanent exchange of perspectives.

Fourth, the results were not stratified by discipline. This may limit the representation of the findings for specific disciplines since the perceived risk factors and, in particular, their perceived priority, may be different.

CONCLUSION

As shown in this paper, injuries in WC alpine ski racing can have various intrinsic and extrinsic risk factors. In order to decrease injury rates in alpine ski racing effectively, a comprehensive perspective might be needed. It is conceivable that a change of one factor alone may not improve the injury problem substantially, and several risk factors have to be approached by prevention interventions. Nevertheless, not all risk factors have the same impact on injury risk. This study compiled and explored those perceived risk factors with the highest believed impact on injury risk. Hence, further studies should verify the plausibility of these factors as true risk factors by using more detailed hypotheses derived from this explorative study.

What this study adds

- This study compiles a list of perceived intrinsic and extrinsic injury risk factors for severe injuries in World Cup alpine ski racing. This list may serve as a guideline for further studies with respect to injuries in alpine ski racing.
- This study explores those perceived risk factors with the highest believed impact on injury risk. With its qualitative character, it provides a base for more detailed hypotheses for further aetiological studies in alpine ski racing.

Acknowledgements We thank all the athletes and coaches, the ski industry, organisers, officials and topic-specific experts for their cooperation and their contributions.

Funding This study was financially supported by the International Ski Federation Injury Surveillance System. The funding source had no involvement in the study design, in the collection, analysis and interpretation data, in the writing of the report, or in the decision to submit this paper for publication.

Competing Interests None

Ethical approval This study was approved by the Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement Additional data from the digital database of the Risk Factor Analysis (RFA) of this study was presented in the unpublished 'FIS report 2010' to the International Ski Federation.

REFERENCES

1. **Florenes TW,** Bere T, Nordsletten L, *et al*. Injuries among male and female World Cup alpine skiers. *Br J Sports Med* 2009;**43**:973–8. doi:10.1136/bjsm.2009.068759.
2. **Ekeland A,** Dimmen S, Lystad H, *et al*. Completion rates and injuries in alpine races during the 1994 Olympic Winter Games. *Scand J Med Sci Sports* 1996;**6**:287–90.
3. **Pujol N,** Blanchi MP, Chambat P. The incidence of anterior cruciate ligament injuries among competitive Alpine skiers: a 25-year investigation. *Am J Sports Med* 2007;**35**:1070–4. doi:10.1177/0363546507301083.
4. **Myklebust G,** Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med* 2005;**39**:127–31. doi:10.1136/bjsm.2004.010900.

5. **Bahr R,** Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med* 2005;**39**:324–9. doi:10.1136/bjsm.2005.018341.
6. **Meeuwisse WH.** Assessing causation in sport injury: a mulitfactorial model. *Clin J Sport Med* 1994;**4**:166–70.
7. **Bere T,** Florenes TW, Krosshaug T, *et al*. Mechanisms of anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. *Am J Sports Med* 2011;**39**:1421–9. doi:10.1177/0363546511405147.
8. **DeMorat G,** Weinhold P, Blackburn T, *et al*. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med* 2004;**32**:477–83. doi:10.1177/0363546503258928.
9. **Krosshaug T,** Slauterbeck JR, Engebretsen L, *et al*. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scand J Med Sci Sports* 2007;**17**:508–19. doi:10.1111/j.1600-0838.2006.00558.x.
10. **Bere T,** Florenes TW, Krosshaug T, *et al*. Events leading to anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases. *Br J Sports Med* 2011;**45**:1294–302. doi:10.1136/bjsports-2011-090517.
11. **Hunter RE.** Skiing injuries. *Am J Sports Med* 1999;**27**:381–9.
12. **Bissell BT,** Johnson RJ, Shafritz AB, *et al*. Epidemiology and risk factors of humerus fractures among skiers and snowboarders. *Am J Sports Med* 2008;**36**:1880–8. doi:10.1177/0363546508318195.
13. **Kirkpatrick AW,** McBeth PB, Ball CG, *et al*. Alpine ski and snowboarding traumatic injuries: incidence, injury patterns, and risk factors for 10 years. *Am J Surg* 2009;**197**:560–4. doi:10.1016/j.amjsurg.2008.12.016.
14. **Sulheim S,** Holme I, Rodven A, *et al*. Risk factors for injuries in alpine skiing, telemark skiing and snowboarding—case-control study. *Br J Sports Med* 2011;**45**:1303–9. doi:10.1136/bjsports-2011-090407.
15. **Niessen W,** Müller E. Carving—biomechanische Aspekte bei der Verwendung stark taillierter Skier und erhöhter Standflächen im alpinen Skisport. *Leistungssport* 1999;**1**:39–44.
16. **Fauve M,** Rhyner HU, Schneebeli M. *Preparation and maintenance of pistes—the handbook for practitioners*. Davos: Swiss Federal Institute for Snow and Avalanche Research, 2002.
17. **FIS.** FIS International Ski Competition Rules ICR 2008. 2008; http://www.fis-ski.com/data/document/icr2008.pdf
18. **Müller E,** Schwameder H. Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J Sports Sci* 2003;**21**:679–92. doi:10.1080/0264041031000140284.
19. **Raschner C,** Schiefermüller C, Zallinger G, *et al*. Biomechanische Analyse der Carvingtechnik als Grundlage modifizierter Trainingsmethoden in der konditionellen Vorbereitung alpiner Ski- und Skrennläufer. *Spectrum* 2001;**13**(Suppl):91–7.
20. **Dicicco-Bloom B,** Crabtree BF. The qualitative research interview. *Med Educ* 2006;**40**:314–21. doi:10.1111/j.1365-2929.2006.02418.x.
21. **Fontana A,** Frey JH. The interview: from structered questions to negotiated text. In: Denzin NK, Lincoln YS. eds. *Collecting and interpreting qualitative materials*. Thousand Oaks, CA: Sage Publications, 2003.
22. **Myers MD,** Newman M. The qualitative interview in IS research: examining the craft. *Info Organ* 2007;**17**:2–26.
23. **Fuller CW,** Ekstrand J, Junge A, *et al*. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br J Sports Med* 2006;**40**:193–201. doi:10.1136/bjsm.2005.025270.
24. **Renshaw AA,** Mote CD. A model for the turning snow ski. *Int J of Mech Sci* 1989;**31**:721–36.
25. **Howe J.** *The new skiing mechanics*. 2nd edn. Waterford: McIntire Publishing, 2001.
26. **Lind D,** Sanders SP. *The physics of skiing—skiing at the triple point*. New York: Springer Verlag, 2004.
27. **Mössner M,** Heinrich D, Kaps P, *et al*. Effects of ski stiffness in a sequence of ski turns. In: Müller E, Lindinger S, Stöggl T. eds. *Science and skiing IV*. Maidenhead: Meyer & Meyer Sport (UK) Ltd., 2009.
28. **Murphy DF,** Connolly DA, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. *Br J Sports Med* 2003;**37**:13–29.
29. **Simoneau M,** Begin F, Teasdale N. The effects of moderate fatigue on dynamic balance control and attentional demands. *J Neuroeng Rehabil* 2006;**3**:22. doi:10.1186/1743-0003-3-22.
30. **Brisswalter J,** Arcelin R, Audiffren M, *et al*. Influence of physical exercise on simple reaction time: effect of physical fitness. *Percept Mot Skills* 1997;**85**(Pt 1):1019–27.

4.3 Part 3: Injury Prevention in Alpine Ski Racing

4.3.1 Paper 5

Preliminary Paper:

Spörri J, Kröll J, Schiefermüller C, Müller E. The influence of course setting on kinematic and kinetic variables related to injury risk. In: Müller E, Lindinger S, Stöggl T, Pfusterschmied J, editors. Book of Abstracts, 5th International Congress on Science and Skiing, St.Christoph am Arlberg (AUT). 2010: p. 108.

THE INFLUENCE OF COURSE SETTING ON KINEMATIC AND KINETIC VARIABLES RELATED TO INJURY RISK

Jörg Spörri, Josef Kröll, Christian Schiefermüller and Erich Müller

Christian Doppler Laboratory Biomechanics in Skiing, Univ. of Salzburg, AUT

KEY WORDS: course setting, injury prevention, alpine ski racing

INTRODUCTION: Using a qualitative research process after interviewing different groups of interest from the World Cup circuit, Spörri et al, 2010 determined that "speed and course setting aspects" was one of the top five high loading key risk factors for injuries. Thereby, course setting interventions have been discussed as a tool to control speed and injury risk among the skiing community. However experience has shown that a tighter set course is not in every case the key for risk reduction. If a turn can be carved and no skidding is provoked by the course set, speed control is not very effective, and higher forces with greater risk can occur. This study investigated the influence of a constant course setting modification over a five gate section within a 15 gate run on kinematic and kinetic variables related to injury risk.

METHOD: During a full 3D kinematic field measurement, using a system of 5 panned, tilted and zoomed cameras (50 Hz) time synchronized by a gen-lock signal, a World Cup racer and an European Cup racer performed in total 16 runs at two different course settings (26 m vertical, 10 m/12 m horizontal distance). A body segment model and geodetic measured reference points were manually digitized in each frame. The 3D position data were then calculated in *PEAK MOTUS* using a Panning Algorithm. Ground reaction forces were measured with the *PEDAR Insole System* of Novel at 100 Hz. For each course setting the variables centre of mass (COM) line, COM speed, COM Radius and skid angle were compared for one turn cycle. Two turn cycles were used for total ground reaction forces.

RESULTS and DISCUSSION: Both course settings provoked drifted turns with similar average skid angles (β) at the first part of the turn cycle. There were clear differences in timing and placement of the COM line, in traverse angle and in turn radius characteristic. However, there were only very small differences found for total ground reaction forces (F_z) and in COM speed (v). This is remarkable due to the fact that a tighter course set with the same speed is thought to generate higher forces on the racer. One explanation could be that forces are reduced continuously by the ski skidding while drifting. Carved turns, measured at the turn cycle before the kinematic measurement area, were also not significantly different for total ground reaction forces. The two course settings used in this study represent the two extremes of the course setting spectrum, common in World Cup Racing for similar conditions. These findings indicate that racers were able to adapt and to compensate for course setting changes used in this study without having to change their overall speed and generated forces.

Table 1. Differences between fast and slow trials

Course	β_{mean}(°)	$F_{z,mean}$(N)	$F_{z,max}$(N)	v_{mean}(m/s)	v_{max}(m/s)
26/12 m	18.35°	1218	2123	17,30	17,94
26/10 m	19.52	1157	2047	17,64	18,24

CONCLUSION: Changes in horizontal gate distances seem not to be very effective for speed control or for influencing variables related to injury risk. However, alterations in vertical distances and "intelligent" course setting which locally slows down a racer, perhaps in a radical manner, before terrain changes or key sectors for example might be an effective way to reduce speed. Hence, these aspects could be investigated systematically for several gates or different gate combinations in order to provide more general information to control speed and minimize the risk for injury to World Cup racers.

REFERENCES

Spörri J, Kröll J, Blake O, Amesberger G, Müller E. (2010). A qualitative approach to determine key injury risk factors in alpine ski racing. Research Report by University of Salzburg mandated by FIS.

4.3.2 Paper 6

Peer-Reviewed Article:

Spörri J, Kröll J, Schwameder H, Schiefermuller C, Müller E. Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *Br J Sports Med*. 2012;46(15):1072-77. doi:10.1136/bjsports-2012-091425.

OPEN ACCESS

Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study

Jörg Spörri, Josef Kröll, Hermann Schwameder, Christian Schiefermüller, Erich Müller

▸ Additional supplementary files are published online only. To view these files please visit the journal online (http://dx.doi.org/10.1136/bjsports-2012-091425).

Department of Sport Science and Kinesiology, Christian Doppler Laboratory: Biomechanics in Skiing, University of Salzburg, 5400 Hallein-Rif, Austria

Correspondence to
Jörg Spörri, Department of Sport Science and Kinesiology, Christian Doppler Laboratory: Biomechanics in Skiing, University of Salzburg, Schlossallee 49, 5400 Hallein-Rif, Austria; joerg.spoerri@sbg.ac.at

Accepted 16 August 2012
Published Online First 14 September 2012

ABSTRACT

Background Course setting has often been discussed as a potential preventative measure in the World Cup ski-racing community. However, there is limited understanding of how it is related to injury risk.

Objective This study was undertaken to investigate the effect of increased horizontal gate distance on energy-related and injury mechanism-related variables.

Methods During a video-based three-dimensional (3D)-kinematic field measurement, a top world-class racer performed giant slalom runs at two course settings with different horizontal gate distances. A full-body segment model was reconstructed in 3D and selected biomechanical parameters were calculated.

Results For the analysed turn, no significant differences were found in turn speed for increased horizontal gate distance. However, a large effect size was observed for speed reduction towards the end of the turn. Turn forces were by tendency higher at the beginning and significantly higher towards the end of the turn. Additionally, significant differences were found in higher inward leaning, and large effect sizes were observed for a decreased fore/aft position after gate passage.

Conclusions On the basis of the data of this study, no final conclusion can be made about whether, for a section of consecutive turns, increasing horizontal gate distance is an effective tool for speed reduction. However, this study pointed out two major drawbacks of this course setting modification: (1) it may increase fatigue as a consequence of loading forces acting over a longer duration; (2) it may increase the risk of out-of-balance situations by forcing the athlete to exhaust his backward and inward leaning spectrum.

INTRODUCTION

Injuries in alpine skiing have been a serious concern since the very beginning of the sport. Assessed over many decades, incidence, severity, aetiology and injury prevention strategies for recreational skiers are well documented.[1–13] In contrast, there are only a few papers addressing the area of elite competitive ski racing.[14–18]

Data by the International Ski Federation (FIS) Injury Surveillance System (ISS) illustrated an alarmingly high injury risk for World Cup (WC) alpine ski racers. Over the WC seasons 2006/2007 and 2007/2008 injury rates of 36.7 per 100 athletes were reported.[15] The most commonly injured body part was found to be the knee (35.6%), and the rupture of the anterior cruciate ligament (ACL) was the most frequent specific diagnosis.[15] Recently, three distinctive mechanisms of ACL injuries in WC ski racing were identified: 'slip-catch', 'dynamic snowplough' and 'landing back weighted'.[17] Characteristically, for the 'slip-catch' and 'dynamic snowplough' mechanisms, the racer initially lost balance backward and inward. Then, while trying to regain grip, the inside edge of either the outer or inner ski caught abruptly in the snow, forcing the knee into valgus and internal rotation. In order to reduce the risk of these injury mechanisms, measures that can reduce the energy involved in the injury situations, may be effective prevention clues.[17 18] Moreover, high skiing speeds, large forces and critical factors that contribute to out-of-balance situations were suggested to play a central role in ACL injury mechanisms.[17 18]

One potential preventative measure that approaches the energy involved and that is widely discussed among the ski racing community, is course setting.[19] Course setting has already been shown to influence skiers' energy in an earlier study of alpine skiing technique in slalom.[20] In the context of injury prevention, course setting became even more important with the introduction of side cut to racing skis, which allowed the racers to carve tighter turns with less friction and to retain speed in situations where previously they skidded and lost speed.[21] In an attempt to keep speed within a safe range in giant slalom (GS), horizontal gate distances became apparently greater over the last decade and the racers had to turn more out of the direction of the fall line. However, it is neither obvious how increased horizontal gate distance influences energy-related variables such as turn speed, nor how it effects injury mechanism-related variables like acting forces and uncontrolled backward and/or inward leaning. The current study is the first study to address this topic in the context of injury prevention; therefore, the purpose of this explorative case study was to investigate the effect of increased horizontal gate distance on energy-related and injury mechanism-related variables in GS.

METHODS

Data collection

During a three-dimensional (3D) kinematic field measurement using a system of five panned, tilted and zoomed video cameras (50 Hz, time synchronised by a gen-lock signal) a top world-class racer performed a total of 12 runs on an injected 15 gate course. After six gates accelerating the racer up to average GS speeds, the racer entered a five-gate section with constant slope inclination of 27.5°. Within this section, gate distances were modified after the first six runs. Initial gate distances were

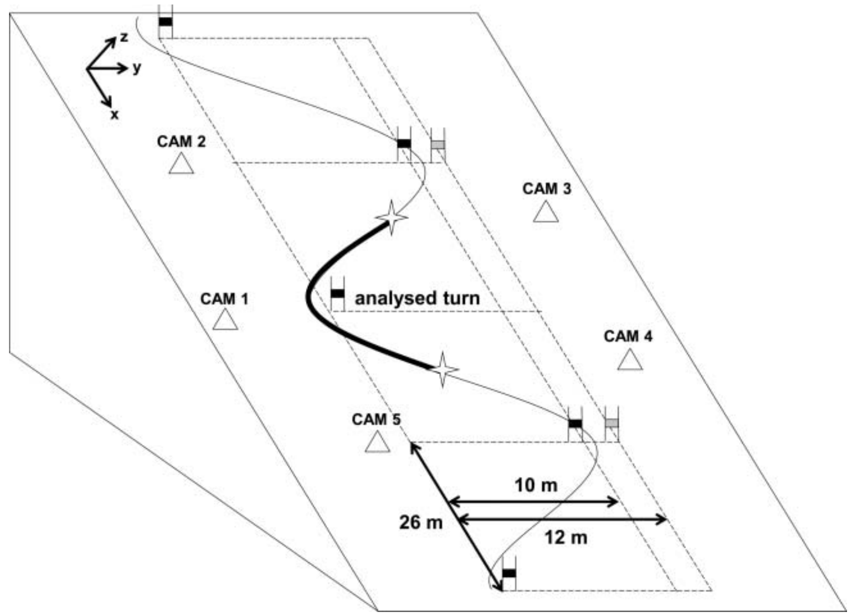


Figure 1 Schema of the measurement setup (CAM 1–5: positions of the panned, tilted and zoomed camcorders).

26 m in vertical direction with an offset of 12 m and were changed for another six runs to 26/10 m (figure 1). These two course settings represent the two extremes of the horizontal gate distance spectrum, common for similar conditions in WC ski racing. In order to determine the skier's 3D position data, a total of 78 reference points were geodetically measured and used to calibrate a capture volume corridor of 52×12×2 m around the analysed turn, which was situated in the middle of the modified five-gate section (figure 1). A 28-point body segment model and the three best visible geodetic measured reference points were manually digitised in each frame of each camera. Joint centres of the segment model were defined according to de Leva.[22] Finally, the skier's segment model was reconstructed in 3D, using the software *PEAK MOTUS* and a direct linear transformation (DLT)-based Panning Algorithm by Drenk.[23]

Parameter calculation

Parameter calculation was performed using the software *MATLAB R2009b*. Centre of mass (COM) was calculated based on the model of Clauser *et al*,[24] adapted with the skiing equipment. Based on the COM line deviations, COM turn radius (R_{COM}) and COM speed (v_{COM}) were calculated numerically.[25] As proposed by Supej *et al*,[26] the crossing points of the COM line projected to the slope plane and the ski line were defined as the beginning (a) and end (e) of the turn (figure 2). Furthermore, the first point where R_{COM} was ≤30 m (b), the point where the COM passed the gate (c) and the last point where R_{COM} was ≤30 m (d) were defined according to Reid *et al*[27] with the R_{COM}-criterion adapted for GS. Based on these five characteristic points of the COM line and ski line, turns were divided into four turn phases and their percentages during the whole turn cycle were calculated: *Initiation (a→b)*, *COM Direction Change I (b→c)*, *COM Direction Change II (c→d)* and *Completion (d→e)* (figure 2). For the calculation of the lean angle (λ_{Lean}) and fore/aft position ($d_{Fore/Aft}$), a local coordinate system (x′y′z′) at the ankle joint of the outside ski was used, as proposed by Schiefermüller *et al*[28] (figure 3). x′ was defined by the joint ankle and the direction of the longitudinal axis of the ski. z′ was defined to be perpendicular to the slope plane and y′ was defined as forming a right-handed triad with x′ and z′. λ_{Lean} was then calculated as the angle between the z-axis and the ski-COM vector projected to the y–z plane (figure 3). $d_{Fore/Aft}$ was defined as the cosine of the fore/aft angle, which is the angle between the z-axis and the ski-COM vector projected to the x–z plane (figure 3). Instant relative centripetal force (F_{cp}) was calculated based on v_{COM} and R_{COM}.

Statistical analysis

Owing to the explorative character of this study, the following steps of statistical analysis were performed: (1) turn average and peak values of the selected parameters were described with

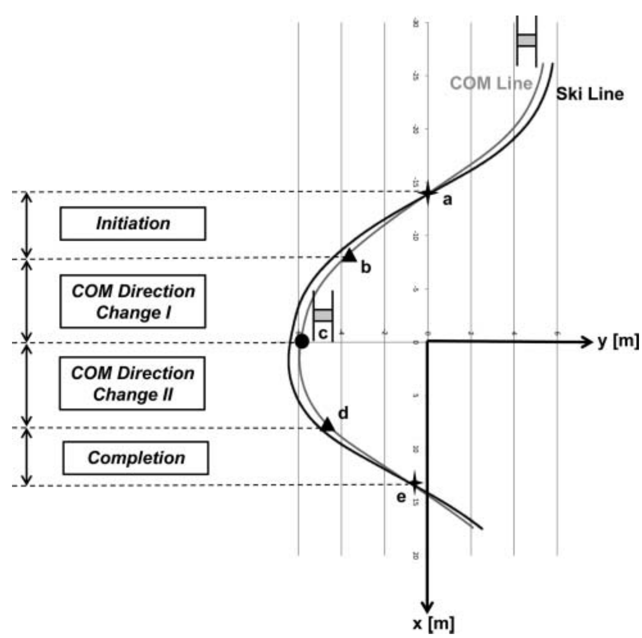


Figure 2 Definition of characteristic line points and turn phases: (COM) centre of mass; (a) beginning of the turn (crossing points of the COM line projected to the slope plane and the ski line); (b) first point where COM turn radius ≤30 m; (c) point where the COM passes the gate; (d) last point where COM turn radius ≤30 m; (e) end of the turn (crossing points of the COM line projected to the slope plane and the ski line).

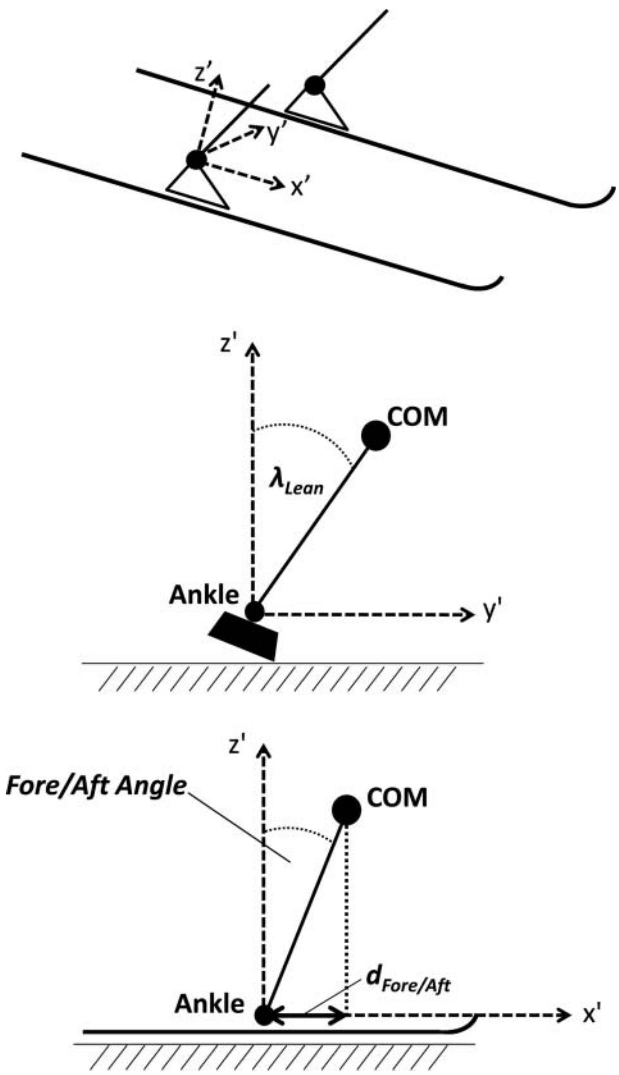


Figure 3 Parameter definition using a local coordinate system at the ankle joint of the outside ski: COM, centre of mass; λ_{Lean}, lean angle; $d_{Fore/Aft}$, fore/aft position.

mean±SD, and differences between the two course settings were determined using several unpaired t tests ($p<0.05$) and effect sizes (Cohen's d); (2) the uncertainty around the estimate of the mean was visualised as the area between the SE boundaries, and potential differences were located with respect to the specific functional phases of the turn; (3) potential differences in specific functional turn phases were tested for significance using several unpaired t tests ($p<0.05$) and effect sizes (Cohen's d).

RESULTS

Differences over the entire turn cycle

The statistics comparing the two course settings with regard to parameter differences over the entire turn cycle are presented in table 1. Regarding v_{COM}, no significant differences in turn averages and peak values were found for the analysed turn. However, for increased horizontal gate distances, a medium effect for higher v_{COM} turn averages was observable. Furthermore, on the 26/12 m course, large effect sizes were observed for higher average F_{cp}, lower average $d_{Fore/Aft}$ and lower minimum $d_{Fore/Aft}$. A significant difference was found in higher average λ_{Lean}. With respect to v_{COM}, the difference between exit speed and entrance speed ($v_{out}-v_{in}$) differed by 0.32 m/s in mean (26/10 m: 0.41±0.58; 26/12 m: 0.09±0.71, d=0.476).

Table 1 Mean±SD and Cohen's d for turn averages and peak values of selected parameters related to injury risk at two different course settings

	26/10 m course (mean±SD)	26/12 m course (mean±SD)	Effect sizes (Cohen's d)
Turn averages			
$v_{COM}^{(Turn)}$ (m/s)	17.63±0.23	17.47±0.32	0.564
$F_{cp}^{(Turn)}$ (N/BW)	1.14±0.03	1.18±0.04	1.000
$d_{Fore/Aft}^{(Turn)}$ (m)	0.12±0.04	0.08±0.03	1.011
$\lambda_{Lean}^{(Turn)}$ (°)	42.5±0.3	43.4±0.7*	1.643
Peak values			
$v_{COM}^{(max)}$ (m/s)	18.14±0.21	18.09±0.31	0.174
$F_{cp}^{(max)}$ (N/BW)	2.17±0.20	2.21±0.19	0.199
$d_{Fore/Aft}^{(min)}$ (m)	−0.08±0.03	−0.11±0.04	0.874
$\lambda_{Lean}^{(max)}$ (°)	58.6±1.8	58.9±1.1	0.187

*$p<0.05$, **$p<0.001$, significantly different from 26/10 m course.
d≈0.20, small effect size; d≈0.50, medium effect size; d≈0.80, large effect size.
COM, centre of mass; $d_{Fore/Aft}$, fore/aft position; F_{cp}, relative centripetal force; λ_{Lean}, lean angle; v_{COM}, COM speed.

Differences in parameter progressions

The progressions of the selected parameters for the two course settings cycle are presented in figure 4. For an increased horizontal gate distance, the following potential differences in the selected parameters may exist: (1) decreased v_{COM} during *Completion*; (2) increased F_{cp} during *Initiation* and *Completion* and (3) decreased $d_{Fore/Aft}$ and increased λ_{Lean} during the turn phases after gate passage (*COM Direction Change II* and *Completion*).

Differences over specific turn phases

The statistics comparing the two course settings with regard to parameter differences over specific turn phases are presented in table 2. Regarding v_{COM}, a large effect for a lower phase average was observed during *Completion* on the 26/12 m course. A medium-to-large effect for higher average F_{cp} was found during *Initiation*. Moreover, F_{cp} was significantly increased during *Completion*. For the turn phases after gate passage, a large effect was found for decreased $d_{Fore/Aft}$ on the 26/12 m course and λ_{Lean} was significantly increased.

Differences in turn cycle structure

The horizontal course setting modification changed the athlete's turn cycle structure significantly (figure 5). On the 26/12 m course, the percentage of the turn cycle where R_{COM} was ≤30 m (*COM Direction Change I&II*) was higher than on the 26/10 m course (26/10 m: 58.5±1.9; 26/12 m: 64.8±2.5**, d=2.777).

DISCUSSION

The main findings for increased horizontal gate distances were as follows: (1) v_{COM} was not significantly reduced over the analysed turn cycle; however, a large effect towards speed reduction during *Completion* was observed; (2) F_{cp} was by tendency higher during *Initiation* (medium–large effect) and F_{cp} was significantly increased during *Completion*; (3) large effect sizes were found for a decreased $d_{Fore/Aft}$ during the turn phases after gate passage and for minimum $d_{Fore/Aft}$; (4) λ_{Lean} was significantly increased during the turn phases after gate passage and (5) the

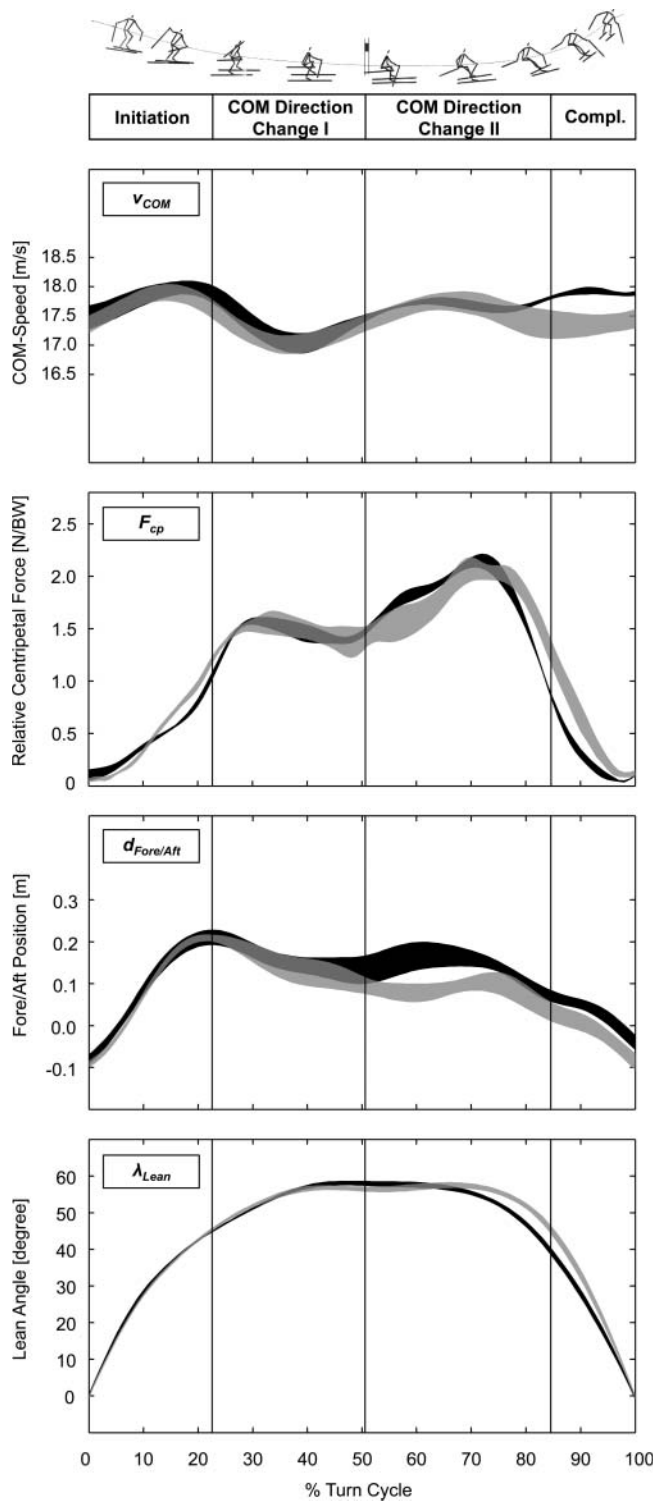


Figure 4 Areas of uncertainty around the estimate of the mean (±SE) for selected parameters related to injury risk at two different course settings; grey: 26/12 m course; black: 26/10 m course. COM, centre of mass; $d_{Fore/Aft}$, fore/aft position; F_{cp}, relative centripetal force; v_{COM}, COM speed; λ_{Lean}, lean angle.

turn cycle structure was significantly changed towards a longer *COM Direction Change*.

Course setting and speed control

Despite a substantial increase in horizontal gate distance, v_{COM} was not significantly reduced over the analysed turn cycle (table 1). However, looking at the progression of v_{COM} within the turn cycle, it is obvious that during *Initiation* and *COM Direction Change I&II*, v_{COM} remained more or less unchanged, while during *Completion*, v_{COM} was reduced (figure 4 and table 2). Consequently, the differences in v_{COM} might be negligible for the analysed turn, although they might have more influence on the following section. Under the assumption that, for the following turns, speed would be reduced by the same rate of $v_{out}-v_{in}$ as in the analysed turn (0.32 m/s), a substantial speed reduction would be already accumulated after a couple of gates. However, recent studies showed that, owing to tactical reasons, skiers with high v_{in} were losing disproportionally more speed than skiers with low v_{in} while turning.[29 30] As a result, it is questionable as to whether the observed effects in v_{COM} would be accumulated over several consecutive turns. Hence, based on the current data, it remains speculative as to whether the analysed course setting modification is able to reduce speed substantially or not. However, further studies with wearable measurement systems capturing several turns per run may provide a deeper understanding of this important question.

Table 2 Mean±SD and Cohen's d for turn phase averages of selected parameters related to injury risk at two different course settings

	26/10 m course (mean±SD)	26/12 m course (mean±SD)	Effect sizes (Cohen's d)
$v_{COM}^{(Completion)}$ (m/s)	17.88±0.10	17.36±0.52	1.304
$F_{cp}^{(Initiation)}$ (N/BW)	0.43±0.05	0.46±0.04	0.700
$F_{cp}^{(Completion)}$ (N/BW)	0.37±0.07	0.64±0.21*	1.615
$d_{Fore/Aft}^{(COM\ Direction\ Change\ II\ \&\ Completion)}$ (m)	0.11±0.04	0.06±0.04	1.309
$\lambda_{Lean}^{(COM\ Direction\ Change\ II\ \&\ Completion)}$ (°)	44.4±1.0	46.6±1.6*	1.628

*$p<0.05$, **$p<0.001$, significantly different from 26/10 m course.
d≈0.20, small effect size; d≈0.50, medium effect size; d≈0.80, large effect size.
COM, centre of mass; F_{cp}, relative centripetal force; $d_{Fore/Aft}$, fore/aft position; λ_{Lean}, lean angle; v_{COM}, COM speed.

Course setting and parameters related to ACL injury mechanisms

While the increase in horizontal gate distance had only a marginal effect on F_{cp} peak values (table 1), F_{cp} was by tendency higher during *Initiation* and F_{cp} significantly increased during *Completion* on the 26/12 m course (table 2.) In the context of injury risk, this means that due to a longer substantial change of direction high loading forces are acting over a longer duration of the turn cycle, which might increase the athlete's fatigue. Since high external loads and fatigue are known to have a negative impact on balance control,[31 32] this may increase the risk for an out-of-balance situation or a fall to occur.

Out-of-balance situations, backward and/or inward, are known to lead to ACL-injury mechanisms.[17] Regarding balance control in the direction fore/aft, $d_{Fore/Aft}$ was not significantly different; however, it did show a clear trend towards a reduced forward position during the turn phases after gate passage and in minimum values at the end of the turn on the 26/12 m course (table 2). Concerning the lateral direction, λ_{Lean} was significantly higher during the turn phases after gate passage for the 26/12 m course setting intervention (table 1). Consequently, there are fewer buffers to critical backward and inward positions on the 'tighter' 26/12 m course set, and the racer is forced to use his full backward and inward leaning capacities. Based on these findings, the risk for an out-of-balance

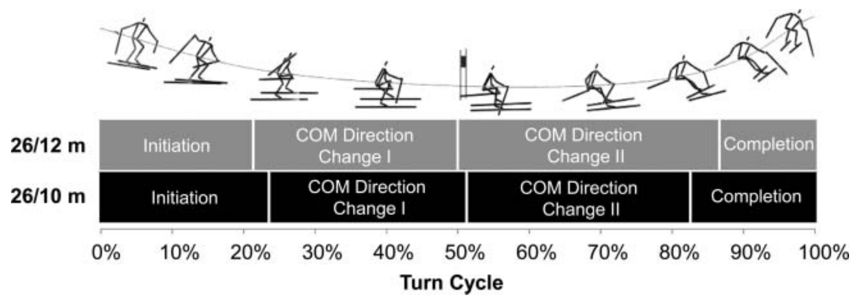


Figure 5 Turn cycle structures as a measure for the athletes timing at the two different course settings. COM, centre of mass.

situation backward and/or inward tends to be higher for the 26/12 m course than for the 26/10 m.

However, maintaining balance in a biomechanical sense is, from the perspective of motor control, not a static, but rather a dynamic task. Therefore, a deeper understanding of the events leading up to an out-of-balance situation might be found in the variability of the motor system. From a dynamic systems perspective, balance may be ensured best by maintaining a central/front position with low variability of COM changes (control variable) while having high variability regarding the joint movements and segment positions (input variables).[33 34] An interesting finding in this context is that towards the end of the turn, wider areas of uncertainty around the estimate of the mean (±SE) were observed for v_{COM}, F_{cp} and $d_{Fore/Aft}$ on the 26/12 m course (figure 4). This may be interpreted as a trend for higher variability in the racer's movement pattern on the course with increased horizontal gate distances. Hence, looking at variability aspects of movement might be a promising approach for further studies in the context of injury mechanisms related out-of-balance situations in alpine ski racing.

Course setting and athlete's timing characteristics

Although on a first view the athlete's timing characteristics seem not to be directly related to injury risk, the differences in turn cycle structure may provide a deeper understanding of the mechanisms underlying the selected parameters related to injury risk. On the 26/12 m course, turn cycle structure was significantly changed towards a higher percentage of the turn cycle where R_{COM} was ≤30 m (*COM Direction Change I&II*). This change of the athlete's strategy might explain the fact that v_{COM} remains more or less unchanged over a wide section of the turn cycle, while during *Completion*, speed was lower for increased horizontal gate distance (figure 4). Owing to a longer *COM Direction Change I&II* the racer might be able to compensate for the course setting changes without having to change the average amount of energy dissipation over a wide range of the turn cycle. However, towards the end of the turn, the later termination of *COM Direction Change II* and the shorter distance to the next gate may force the athlete to perform more at his limit, making him more susceptible to technical mistakes. Furthermore, at the end of the turn, the shorter duration where R_{COM} is >30 m (*Completion*) may limit the racer's speed uptake due to a shorter straight transition of COM. Hence, these aspects may serve as an explanation for the lower speed towards the end of the turn and the higher variability in v_{COM}, F_{cp} and $d_{Fore/Aft}$ on 26/12 m course.

Methodological considerations

Study design

At first glance, one limitation of the present study might be the fact that for the analysis, the focus was only on one subject. This choice can be considered from two different perspectives: On the one hand, analysing more subjects would strengthen the possibilities for generalising the results. On the other hand, using a single subject design reduced the variability between the single trials; therefore, it increased the power to detect differences between the two course settings. Furthermore, it has to be pointed out that different course settings can be adapted by athletes with different individual strategies regarding line and timing. This directly influences the variables related to injury risk. An individual-subject-analysis design is needed when the variations in movement are the result of different strategies to perform the same task by individual subjects, and not the result of more or less variations among individuals.[35] Accordingly, the use of an individual-subject-analysis design can be argued to be appropriate for the present explorative research question.

Data collection

The reliability and accuracy of the method that was used for collecting kinematic data in the field have been shown to be comparable to laboratory conditions in an earlier study.[36] However, measuring 3D kinematics in alpine ski racing under field conditions is affected by changing snow conditions and an athlete's fatigue due to repetitive runs, wind, temperature and solar radiation. This limits the time where the environmental conditions are constant and, therefore, the maximal number of reliable trials. However, the time period of 3 h used in this study had nearly constant meteorological conditions and the total of 12 trials on the same course was, therefore, in an acceptable range regarding these limitations.

Statistical analysis

A further limitation of the study was the small data sample that was used for the statistical analysis of differences between the two course settings. However, provided that the variability between the trials was small and that for the interpretation of the results effect sizes (Cohen's d) were also considered, this procedure may be justified for the purpose of an explorative case study.

CONCLUSION

On the basis of the data of this study, no final conclusion can be made whether, for a section of consecutive turns, increasing horizontal gate distance is an effective tool for speed reduction. Therefore, further studies using wearable measurement systems should investigate this aspect more systematically for several gates, different gate combinations and/or under race conditions. Nevertheless, the current study illustrated that as long as the course setting changes are not substantial enough, speed might not be reduced considerably, since racers are still able to adapt and partly compensate by changing their timing strategy. Moreover, the study pointed out two major safety drawbacks

WHAT THIS STUDY ADDS

- For a considerably speed reduction by increasing the horizontal gate distances, substantial course setting changes might be needed, since racers are able to adapt and partly compensate by changing their timing strategy.
- There might be two safety drawbacks of controlling speed by increased horizontal gate distances: (1) increased fatigue and (2) higher risk of out-of-balance situations.

of controlling speed by consecutively increasing horizontal gate distances: (1) it may increase fatigue due to a longer substantial change of direction and high loading forces acting over a longer duration of the turn cycle and (2) it may increase the risk of out-of-balance situations by forcing the athlete to exhaust his backward and inward leaning spectrum. Hence, course settings that locally slow down a racer (perhaps in a substantial manner) before terrain changes or key sectors, or alterations in vertical gate distance might be a more appropriate way to reduce speed without the aforementioned drawbacks.

Contributors All authors fulfil the criteria of authorship and were involved in: (1) conception and design, acquisition of data or analysis and interpretation of data; (2) drafting the article or revising it critically for important intellectual content and (3) final approval of the version published.

Funding This study was financially supported by the International Ski Federation (FIS) Injury Surveillance System (ISS).

Competing interests None.

Ethical approval This study was approved by the Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1. **Laporte JD,** Binet MH, Constans D. Evolution of ACL ruptures in French ski resorts 1992–1999. *Skiing Trauma Safety*, 13th Vol. 2000;**1397**:95–107.
2. **Kirkpatrick AW,** McBeth PB, Ball CG, *et al*. Alpine ski and snowboarding traumatic injuries: incidence, injury patterns, and risk factors for 10 years. *Am J Surg* 2009;**197**:560–4.
3. **Johnson RJ,** Ettlinger CF, Shealy JE. Update on injury trends in alpine skiing. *Skiing Trauma Safety* 2009;**1510**:11–22.
4. **Ekeland A,** Rodven A. Injury trends in Norwegian ski resorts in the 10 year period 1996–2006. *Skiing Trauma Safety* 2009;**1510**:31–8.
5. **Viola RW,** Steadman JR, Mair SD, *et al*. Anterior cruciate ligament injury incidence among male and female professional alpine skiers. *Am J Sports Med* 1999;**27**:792–5.
6. **Howe J,** Johnson RJ. Knee injuries in skiing. *Clin Sports Med* 1982;**1**:277–88.
7. **Ekeland A,** Thoresen B. Isolated rupture of the anterior cruciate ligament by knee hyperflexion. *Skiing Trauma Safety* 1987;**938**:61–7.
8. **Jarvinen M,** Natri A, Laurila S, *et al*. Mechanisms of anterior cruciate ligament ruptures in skiing. *Knee Surg Sports Traumatol Arthrosc* 1994;**2**:224–8.
9. **Ettlinger CF,** Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med* 1995;**23**:531–7.
10. **Hunter RE.** Skiing injuries. *Am J Sports Med* 1999;**27**:381–9.
11. **DeMorat G,** Weinhold P, Blackburn T, *et al*. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med* 2004;**32**:477–83.
12. **Mote CD.** The forces of skiing and their implication to injury. *Int J Sport Biomech* 1987;**3**:309–25.
13. **Bissell BT,** Johnson RJ, Shafritz AB, *et al*. Epidemiology and risk factors of humerus fractures among skiers and snowboarders. *Am J Sports Med* 2008;**36**:1880–8.
14. **Pujol N,** Blanchi MP, Chambat P. The incidence of anterior cruciate ligament injuries among competitive alpine skiers: a 25-year investigation. *Am J Sports Med* 2007;**35**:1070–4.
15. **Florenes TW,** Bere T, Nordsletten L, *et al*. Injuries among male and female World Cup alpine skiers. *Br J Sports Med* 2009;**43**:973–8.
16. **Krosshaug T,** Slauterbeck JR, Engebretsen L, *et al*. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scand J Med Sci Sports* 2007;**17**:508–19.
17. **Bere T,** Florenes TW, Krosshaug T, *et al*. Mechanisms of anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases. *Am J Sports Med* 2011;**39**:1421–9.
18. **Bere T,** Florenes TW, Krosshaug T, *et al*. Events leading to anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases. *Br J Sports Med* 2011;**45**:1294–302.
19. **Spörri J,** Kröll J, Amesberger G, *et al*. Perceived key injury risk factors in World Cup alpine ski racing—an explorative qualitative study with expert stakeholders. *Br J Sports Med*. Published Online First 9 August 2012. doi: 10.1136/bjsports-2012-091048
20. **Reid R.** A Kinematic and kinetic study of alpine skiing technique in Slalom (PhD thesis). Dissertation,: Oslo: Norwegian School of Sport Sciences, 2010, ISBN Nr. 978-82-502-0440-9.
21. **Sahashi T,** Ichino S. Carving-turn and edging angle of skis. *Sports Eng* 2001;**4**:135–45.
22. **de Leva P.** Joint center longitudinal positions computed from a selected subset of Chandler's data. *J Biomech* 1996;**29**:1231–3.
23. **Drenk V.** Photogrammetric evaluation procedures for pannable and tiltable cameras of variable focal length. *Conference Proceedings ISBS-12 International Symposium on Biomechanics in Sports*; Budapest, 1994:27–30. http://w4.ub.uni-konstanz.de/cpa/article/view/2440 (accessed 7 Aug 2012).
24. **Clauser CE,** Mc Conville JT, Young JW. *Weight, volume and centre of mass segments of the human body*. Wright-Patterson Air force Base, OH, USA, 1969.
25. **Gilat A,** Subramaniam V. *Numerical methods for engineers and scientists*. Hoboken, NJ: John Wiley & Sons, Inc., 2008.
26. **Supej M,** Kugovnik O, Nemec B. Kinematic determination of the beginning of a ski turn. *Kinesiol Slov* 2003;**9**:11–17.
27. **Reid R,** Gilgien M, Morger T, *et al*. Turn characteristics and energy dissipation in slalom. In: Müller E, Lindinger S, Stöggl T, eds. *Science and skiing IV*. Maidenhead: Meyer & Meyer Sport (UK) Ltd., 2009:419–29.
28. **Schiefermüller C,** Lindinger S, Müller E. The skier's centre of gravity as a reference point in movement analyses for different designated systems. In: Müller E, Bacharach D, Klika R, Lindinger S, Schwameder H, eds. *Science and skiing III*. Oxford: Meyer & Meyer Sport (UK), Ltd., 2005:172–85.
29. **Supej M,** Kipp R, Holmberg HC. Mechanical parameters as predictors of performance in alpine World Cup slalom racing. *Scand J Med Sci Sports* 2011;**21**:72–81.
30. **Spörri J,** Kröll J, Schwameder H, *et al*. Turn characteristics of a top world class athlete in giant slalom—a case study assessing current performance prediction concepts. *Int J Sports Sci Coaching*. In press
31. **Simoneau M,** Begin F, Teasdale N. The effects of moderate fatigue on dynamic balance control and attentional demands. *J Neuroeng Rehabil* 2006;**3**:22.
32. **Qu X,** Nussbaum MA. Effects of external loads on balance control during upright stance: experimental results and model-based predictions. *Gait Posture* 2009;**29**:23–30.
33. **Hamill J,** Haddad JM, Heiderscheit BC, *et al*. Clinical relevance of variability in coordination. In: Davids K, Bennett S, Newell K, eds. *Movement system variability*. Leeds: Human Kinetics, 2006:153–65.
34. **Hasan Z.** The human motor control system's response to mechanical perturbation: should it, can it, and does it ensure stability? *J Mot Behav* 2005;**37**:484–93.
35. **Bates BT.** Single-subject methodology: an alternative approach. *Med Sci Sports Exerc* 1996;**28**:631–8.
36. **Klous M,** Müller E, Schwameder H. Collecting kinematic data on a ski/snowboard track with panning, tilting, and zooming cameras: is there sufficient accuracy for a biomechanical analysis? *J Sports Sci* 2010;**28**:1345–53.

5 Conclusions

The purpose of this doctoral thesis was to investigate biomechanical aspects of performance enhancement and injury prevention, two central aspects in the sport of alpine ski racing. The main conclusions with respect to the different project parts (Part 1-3) and the specific aims of the thesis (1-5) were as follows:

Part 1: Performance Enhancement in Alpine Ski Racing

1. *To assess the ability of current performance enhancement concepts to explain time differences within a one turn section.*

Comparing fast and slow GS turns of a top world class racer, none of the current performance prediction/enhancement concepts were able to solely explain the time differences between different performed turns. This might be explained by the fact that these concepts address only isolated aspects of ski racing performance, such as the skier's speed, energy or line. These factors are merely single aspects of a very complex relationship. For a practical application in alpine ski racing, they should be combined into one comprehensive concept balancing the performance related factors among each other. In science, looking at instantaneous performance time might pose new possibilities of combining different influencing factors in one approach. For practice, this might bring new insights into the very complex interaction between technical/tactical aspects and performance, an essential pre-step of performance enhancement.

2. *To compare the characteristics of turns with fast and slow section times of top world class athlete and to address the possibility of their being advantageous.*

The fastest and slowest turn of a top world class athlete mainly differed in the placement of COM line to the gate and the timing within the turn cycle. The fastest turn was initiated higher regarding the vertical position on the slope plane, and was turning less out of the direction of the fall line. As a consequence, a higher percentage of the turn cycle was executed before the turn. These line and timing characteristics are considered to be advantageous, since they require less drifting and, therefore, less energy dissipation prior the gate.

3. *To assess whether similar characteristics can be observed for different course settings.*

Similar line and timing characteristics were observed for other trials and two different course settings representing both extremes of the course setting spectrum for similar conditions in WC alpine ski racing. These findings indicate that line and timing characteristics play a central role for the understanding of the individual and situational compromise between the accelerating and decelerating effects of gravity, as well as energy loss. Moreover, the training of the implicit adaptation mechanisms in terms of situation dependent line/timing strategies might be an essential part in performance orientated technical/tactical training.

Part 2: Injury Risk Factors in Alpine Ski Racing

4. *To compile a list of perceived intrinsic and extrinsic key risk factors for severe injuries in WC alpine ski racing, and to explore them in order to provide more detailed hypotheses for further aetiological studies.*

In total, 32 perceived risk factor categories were derived from expert stakeholders' interviews within the basic categories of Athlete, Course, Equipment, and Snow. With respect to their perceived impact on injury risk, the experts' perceived top five key injury risk factors were:

System, ski binding, plate, and boot
According to the experts' the current equipment is too aggressive and too direct in the ski-snow interaction favouring self-dynamic behaviour of the ski in the case of an uncontrolled out-of-balance situation.

Changing snow conditions
Changing snow conditions, in particular within the same run, were believed to increase the injury risk since it is difficult to set-up and prepare the equipment for all different conditions.

Speed and course setting aspects
Among the experts, course setting was discussed as a potential preventative measure to reduce speed, and therefore, the energy involved. However, in carved turns, speed in combination with small turn radii was believed to result in high turn forces, and as a result increase injury risk. Moreover, the experts' stated that course settings that increase the general amount of skidding might be necessary for an effective speed control.

Physical aspects of the athletes
A lack of physical fitness was suggested to increase the injury risk. While this might be a potential risk factor, in particular for younger athletes, the experts pointed out that at the top WC level, athletes have already reached their limitations and that physical fitness cannot be further improved.

Speed in general
According to the experts, speed is a general risk factor, since it increases the energy involved and decreases the ability of the athlete to react and/or correct mistakes.

Part 3: Injury Prevention in Alpine Ski Racing

5. *To investigate the effect of specific course setting modifications as one potential preventative measure on selected biomechanical variables related to injury risk in alpine ski racing.*

For the analysed turn, no significant differences were found in turn speed for increased horizontal gate distance. In order to considerably reduce speed, more substantial course setting changes might be needed, since the racers are able to adapt and partly compensate by changing their timing strategy. However, controlling speed by increased horizontal gate distance might have two essential safety drawbacks: (1) increased fatigue, and (2) higher risk of out-of-balance situations.

6 Outlook

Based on the current body of knowledge and the findings of this doctoral thesis, future scientific investigation should be focused on the following aspects:

Biomechanical Aspects of Performance Enhancement

Performance in alpine ski racing is from a biomechanical perspective basically influenced by two factors: speed and the choice of line between the gates.[42] While some studies provided theoretical models calculating the "path of the quickest descent" down a course while neglecting the skier's energy dissipation,[13, 24, 40] other studies primarily focused minimising the skier's energy dissipation while neglecting the theoretical aspects of the "path of the quickest descent".[18, 23] However, none of the current performance prediction/enhancement concepts combined these two aspects into one comprehensive concept balancing the performance relevant factors (speed and line) among each other. This shortcoming was illustrated in the current thesis on the example of the turn characteristics of a top world class athlete.

Therefore, future research should focus on the following three steps: (1) finding predictors of performance that account for both speed and the choice of line. One such approach might be found in the time loss per elevation difference *dt/dz*, as suggested by Federolf [42]; (2) assessing these new concepts for their ability to predict overall performance time (= time needed for a certain section or an entire course); and (3) investigating the influence of the skier's movement patterns and line characteristics on those performance predictors which are the most representatives for overall performance. Based on these three steps, it might be possible to define performance enhancement concepts that are more effective for coaching practice than the current concepts. However, it has to be pointed out that for the applicability of performance enhancement research in coaching practice, number 3 above, is the most important and the most challenging step. Without knowing the corresponding skier's movement and/or line characteristics in detail, the information "whether" and "where" time is lost or gained is useless for coaching practice; the central question is the "why".

Biomechanical Aspects of Injury Prevention

With regards to the first step of the sequence of injury prevention research suggested by van Mechelen et al. [46], recent data of the FIS Injury Surveillance System showed an alarmingly high incidence of severe injuries in alpine ski racing.[1] Hence, there is an evident need for improving injury prevention in alpine ski racing. While the understanding of the injury causes (step 2) was substantially improved by recent studies [64-66] and this doctoral thesis, there is still a lack of knowledge with respect to potential preventative measures.

For the perceived preventative measure "course setting", this thesis provided a first explorative step towards a deeper understanding of how it influences biomechanical variables related to injury risk. However, further studies should investigate these aspects more systematically for several gates, different gate combinations or under race conditions. In addition, there is an evident need for the assessment of potential preventative measures within other risk factor areas. Based on the findings of this thesis, other areas with high impact on injury risk might be the equipment (ski, plate, binding and boot), changing snow conditions, physical aspects of the athletes and the skiers speed. Once there is more knowledge in the aforementioned areas available, it might be possible to introduce effective injury prevention strategies to competitive WC alpine skiing (step 3). Finally, these injury prevention strategies should be assessed for their effectiveness by retrospective studies (step 4). Therefore, future injury prevention research should also be focused on a consistent monitoring of the incidence and severity of injuries in competitive WC alpine skiing, and the extension of these statistics on lower levels, such as European Cup or FIS-Races.

A. Appendix

Measurement of Segment Lengths

(according to de Leva[1])

First, joint centres were determined based on the following instruction. Second, joint centres were marked. Third, segment lengths were calculated.

Knee Joint:

- Ski boot joint – Condylus lateralis femoris + 8,9 %
- Trochanter major – Condylus lateralis femoris – 7,4 %

Hip Joint:

- Trochanter major – Condylus lateralis femoris + 0,7 %
- From Trochanter major (outest palpation point) 54 mm medial, 30 mm proximal

Elbow Joint:

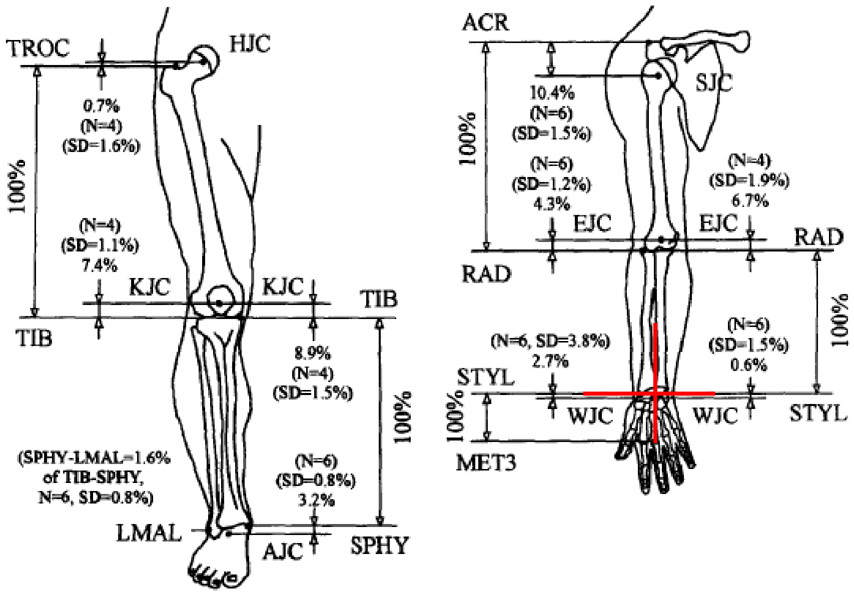
- Acromion – Radius lateral point – 4,3 %
- Epicondylus medialis humeri

Shoulder:

- Acromion – Radius lateral point – 10,4 %

Wrist:

- Intersection point: Processus styloideus radii (outer bone) und Metacarpal III



[1] Leva, P. Joint centre longitudinal positions computed from a selected subset of Chandler's Data. *J Biomech.* 1996;29(9):1231-1233.

B. References

1. Florenes TW, Bere T, Nordsletten L, et al. Injuries among male and female World Cup alpine skiers. *Br J Sports Med*. 2009;43(13):973-8. doi:10.1136/bjsm.2009.068759.

2. Ekeland A, Nordsletten L, Lystad H, et al. Previous skiing injuries in Alpine Olympic racers. *Skiing Trauma and Safety*. 1997;1289:7-13. doi:10.1520/Stp18283s.

3. Polednik H. Das Glück im Schnee. Wien: Amalthea Verlag Ges. m. b. H.; 1991.

4. Suttner J. Die grossen Skisport Stars. München: Copress Verlag GmbH; 1992.

5. Lauterwasser E, Mülbert M, Wagnerberger F, et al. Faszination Skilauf. Heidelberg: Edition Braus; 1995.

6. FIS. Ski History. http://history.fis-ski.com. 2012 [accessed 4. October 2012].

7. Beck N. Ski-Geschichte: Prähistorische Felsgravuren. http://www.skimuseum.li/geschichte/praehistorische-felsgravuren.html. 2012 [accessed 4. October 2012].

8. Olympic-Movement. Alpine skiing Equipment and History. http://www.olympic.org/alpine-skiing-equipment-and-history?tab=history. 2012 [accessed 4. October 2012].

9. FIS. International Competition Rules ICR. http://www.fis-ski.com/data/document/icr-2011july_web.pdf. 2011 [accessed 2. November 2011].

10. HKR-Statistics. Hahnenkamm-Rennen (HKR) - General Facts. http://www.hahnenkamm.com/hkr-statistik.html. 2011 [accessed 4. October 2012].

11. Gadient V, Dannenberger D, Homberger M, et al. Schneesport Schweiz, Band 2: Ski. Belp: SWISS SNOWSPORTS Association (SSSA); 2010.

12. Howe J. The new skiing mechanics. 2nd ed. Waterford: McIntire Publishing; 2001.

13. Lind D, Sanders SP. The Physics of Skiing - Skiing at the Triple Point. New York: Springer Verlag; 2004.

14. Reid R. A Kinematic and Kinetic Study of Alpine Skiing Technique in Slalom [PhD Thesis]. Dissertation, ISBN Nr. 978-82-502-0440-9: Norwegian School of Sport Sciences Oslo; 2010.

15. Wagner G. Messtechnische Differenzierung von gerutschten und geschnittenen Kurven im alpinen Skilauf [Unpublished Diploma-Thesis]: University of Salzburg; 2006.

16. Supej M, Kugovnik O, Nemec B. Kinematic determination of the beginning of a ski turn. *Kinesiologia Slovenica*. 2003;9(1):11-7.

17. Jentschura UD, Fahrbach F. Physics of skiing: the ideal-carving equation and its applications. *Can J Phys*. 2004;82(4):249-61. doi:10.1139/P04-010.

18. Supej M, Kipp R, Holmberg HC. Mechanical parameters as predictors of performance in alpine World Cup slalom racing. *Scand J Med Sci Sports*. 2011;21(6):e72-81. doi:10.1111/j.1600-0838.2010.01159.x.

19. Weineck J. Optimales Training. 14th ed. Balingen: Spitta Verlag GmbH & Co.; 2004.

20. Roithner R. Einfluss von Skilängen und Taillierung auf ausgewählte, kinematische Variablen im alpinen Slalom [Unpublished PhD Thesis]: University of Salzburg; 2004.

21. Breil FA, Weber SN, Koller S, et al. Block training periodization in alpine skiing: effects of 11-day HIT on VO2max and performance. *Eur J Appl Physiol*. 2010;109(6):1077-86. doi:10.1007/s00421-010-1455-1.

22. Draksal M, Salcher B. Mentales Training im Skirennlauf. Leipzig: Draksal Fachverlag; 2006.

23. Reid R, Gilgien M, Morger T, et al. Turn characteristics and energy dissipation in slalom. In: Müller E, Lindinger S, Stöggl T, editors. Science and Skiing IV. Maidenhead: Meyer & Meyer Sport (UK) Ltd.; 2009. p. 419-29.

24. Hirano Y. Quickest descent line during alpine ski racing. *Sports Eng*. 2006;9:221-8.

25. Renshaw AA, Mote CD. A model for the turning snow ski. *Int J of Mech Sci*. 1989;31(10):721-36.

26. Federolf P, Scheiber P, Rauscher E, et al. Impact of skier actions on the gliding times in alpine skiing. *Scand J Med Sci Sports*. 2008;18(6):790-7. doi:10.1111/j.1600-0838.2007.00745.x.

27. Federolf P, JeanRichard F, Fauve M, et al. Deformation of snow during a carved ski turn. *Cold Regions Science and Technology*. 2006;46(1):69-77. doi:DOI 10.1016/j.coldregions.2006.06.006.

28. Yoneyama T, Kitade M, Osada K. Investigation on the ski-snow interaction in a carved turn based on the actual measurement. *Engineering of Sport 8: Engineering Emotion - 8th Conference of*

the International Sports Engineering Association (Isea). 2010;2(2):2901-6. doi:DOI 10.1016/j.proeng.2010.04.085.

29. Heinrich D, Mossner M, Kaps P, et al. Calculation of the contact pressure between ski and snow during a carved turn in Alpine skiing. *Scand J Med Sci Sports*. 2010;20(3):485-92. doi:10.1111/j.1600-0838.2009.00956.x.

30. Barelle C, Ruby A, Tavernier M. Experimental model of the aerodynamic drag coefficient in alpine skiing. *J Appl Biomech*. 2004;20(2):167-76.

31. Meyer F, Le Pelley D, Borrani F. Aerodynamic drag modeling of alpine skiers performing giant slalom turns. *Med Sci Sports Exerc*. 2012;44(6):1109-15. doi:10.1249/MSS.0b013e3182443315.

32. Kaps P, Nachbauer W, Mössner M. Determination of kinetic friction and drag area in alpine skiing. *Skiing Trauma and Safety*. 1996;1266:165-77. doi:10.1520/Stp37926s.

33. Supej M, Saetran L, Oggiano L, et al. Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scand J Med Sci Sports*. 2012. doi:10.1111/sms.12007.

34. Federolf P, Reid R, Gilgien M, et al. The application of principal component analysis to quantify technique in sports. *Scand J Med Sci Sports*. 2012. doi:10.1111/j.1600-0838.2012.01455.x.

35. Berg HE, Eiken O, Tesch PA. Involvement of eccentric muscle actions in giant slalom racing. *Med Sci Sports Exerc*. 1995;27(12):1666-70.

36. Hintermeister RA, O'Connor DD, Dillman CJ, et al. Muscle activity in slalom and giant slalom skiing. *Med Sci Sports Exerc*. 1995;27(3):315-22.

37. Raschner C. Kinematische und dynamische Technikanalyse im Slalom als Grundlage für die Entwicklung skispezifischer Krafttrainingsgeräte und Krafttrainingsmethoden [Unpublished PhD Thesis]: University of Salzburg; 1997.

38. Müller E, Schwameder H. Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *J Sports Sci*. 2003;21(9):679-92. doi:10.1080/0264041031000140284.

39. Pozzo R, Canclini A, Cotelli C, et al. 3D-kinematics and kinetic analysis of G-Slalom in elite skiers at Val Badia World Cup race in 2002. In: Müller E, Bacharach D, Klika R, Lindinger S, Schwameder H, editors. Science and Skiing III. Oxford: Meyer & Meyer Sport (UK) Ltd.; 2004. p. 125-35.

40. Reinisch G. A physical theory of alpine ski racing. *Spectrum der Sportwissenschaften*. 1991;3(1):26-50.

41. Nachbauer W. Fahrlinie in Torlauf und Riesentorlauf. *Leistungssport*. 1987;6:17-21.

42. Federolf PA. Quantifying instantaneous performance in alpine ski racing. *J Sports Sci*. 2012;30(10):1063-8. doi:10.1080/02640414.2012.690073.

43. Supej M. Differential specific mechanical energy as a quality parameter in racing alpine skiing. *J Appl Biomech*. 2008;24(2):121-9.

44. Pujol N, Blanchi MP, Chambat P. The incidence of anterior cruciate ligament injuries among competitive alpine skiers: a 25-year investigation. *Am J Sports Med*. 2007;35(7):1070-4. doi:10.1177/0363546507301083.

45. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med*. 2005;39(3):127-31. doi:10.1136/bjsm.2004.010900.

46. van Mechelen W, Hlobil H, Kemper HCG. Incidence, severity, etiology and prevention of sports injuries - a review of concepts. *Sports Medicine*. 1992;14(2):82-99.

47. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med*. 2005;39(6):324-9. doi:10.1136/bjsm.2005.018341.

48. Meeuwisse WH. Assessing causation in sport injury: a mulitfactorial model. *Clin J Sport Med*. 1994;4:166-70.

49. Fuller CW, Junge A, Dvorak J. Risk management: FIFA's approach for protecting the health of football players. *Br J Sports Med*. 2012;46(1):11-7. doi:10.1136/bjsports-2011-090634.

50. Fuller C, Drawer S. The application of risk management in sport. *Sports Med*. 2004;34(6):349-56.

51. Laporte JD, Binet MH, Constans D. Evolution of ACL ruptures in French ski resorts 1992-1999. *Skiing Trauma and Safety, 13th Vol*. 2000;1397:95-107.

52. Kirkpatrick AW, McBeth PB, Ball CG, et al. Alpine ski and snowboarding traumatic injuries: incidence, injury patterns, and risk factors for 10 years. *Am J Surg*. 2009;197(5):560-4. doi:10.1016/j.amjsurg.2008.12.016.

53. Johnson RJ, Ettlinger CF, Shealy JE. Update on injury trends in alpine skiing. *Skiing Trauma and Safety*. 2009;1510:11-22.

54. Ekeland A, Rodven A. Injury trends in Norwegian ski resorts in the 10 year period 1996-2006. *Skiing Trauma and Safety*. 2009;1510:31-8.

55. Viola RW, Steadman JR, Mair SD, et al. Anterior cruciate ligament injury incidence among male and female professional alpine skiers. *Am J Sports Med*. 1999;27(6):792-5.

56. Howe J, Johnson RJ. Knee injuries in skiing. *Clin Sports Med*. 1982;1(2):277-88.

57. Ekeland A, Thoresen B. Isolated rupture of the anterior cruciate ligament by knee hyperflexion. *Skiing Trauma and Safety*. 1987;938:61-7.

58. Jarvinen M, Natri A, Laurila S, et al. Mechanisms of anterior cruciate ligament ruptures in skiing. *Knee Surg Sports Traumatol Arthrosc*. 1994;2(4):224-8.

59. Ettlinger CF, Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med*. 1995;23(5):531-7.

60. Hunter RE. Skiing injuries. *Am J Sports Med*. 1999;27(3):381-9.

61. DeMorat G, Weinhold P, Blackburn T, et al. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32(2):477-83. doi:10.1177/0363546503258928.

62. Mote CD. The forces of skiing and their implication to injury. *Int J Sport Biomech*. 1987;3(4):309-25.

63. Bissell BT, Johnson RJ, Shafritz AB, et al. Epidemiology and risk factors of humerus fractures among skiers and snowboarders. *Am J Sports Med*. 2008;36(10):1880-8. doi:10.1177/0363546508318195.

64. Krosshaug T, Slauterbeck JR, Engebretsen L, et al. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. *Scand J Med Sci Sports*. 2007;17(5):508-19. doi:10.1111/j.1600-0838.2006.00558.x.

65. Bere T, Florenes TW, Krosshaug T, et al. Mechanisms of anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. *Am J Sports Med*. 2011;39(7):1421-9. doi:10.1177/0363546511405147.

66. Bere T, Florenes TW, Krosshaug T, et al. Events leading to anterior cruciate ligament injury in World Cup Alpine Skiing: a systematic video analysis of 20 cases. *Br J Sports Med*. 2011;45(16):1294-302. doi:10.1136/bjsports-2011-090517.

67. Müller E, Schiefermüller C, Kröll J, et al. Skiing with carving skis - what is new? In: Müller E, Bacharach D, Klika R, Lindinger S, Schwameder H, editors. Science and Skiing III. Oxford: Meyer & Meyer Sport (UK), Ltd.; 2005. p. 15-23.

68. Niessen W, Müller E. Carving - biomechanische Aspekte bei der Verwendung stark taillierter Skier und erhöhter Standflächen im alpinen Skisport. *Leistungssport*. 1999;1:39-44.

69. Hamill J, Haddad JM, Heiderscheit BC, et al. Clinical relevance of variability in coordination. In: Davids K, Bennett S, Newell K, editors. Movement System Variability. Leeds: Human Kinetics; 2006.

70. Schiefermüller C. Kinematische Feldforschung im alpinen Schilauf - Vergleich unterschiedlicher Systeme zur dreidimensionalen Punkterfassung [Unpublished PhD Thesis]: University of Salzburg; 2009.

71. Müller E, Bartlett R, Raschner C, et al. Comparisons of the ski turn techniques of experienced and intermediate skiers. *J Sports Sci*. 1998;16(6):545-59. doi:10.1080/026404198366515.

72. Klous M, Muller E, Schwameder H. Three-dimensional Knee Joint Loading in Alpine Skiing: A comparison Between a Carved and a Skidded Turn. *J Appl Biomech*. 2012.

73. Klous M, Müller E, Schwameder H. Collecting kinematic data on a ski/snowboard track with panning, tilting, and zooming cameras: is there sufficient accuracy for a biomechanical analysis? *J Sports Sci*. 2010;28(12):1345-53. doi:10.1080/02640414.2010.507253.

74. Brodie M, Walmsley A, Page W. Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing. *Sports Technol*. 2008;1(1):17-28.

75. Brodie M, Walmsley A, Page W. Fusion Motion Capture: Can technology be used to optimise alpine ski racing technique? *Impact of Technology on Sports Ii*. 2008:825-31.

76. Supej M. A step forward in 3D measurements in alpine skiing: a combination of inertial suit and DGPS technology. In: Müller E, Lindinger S, Stöggl T, editors. Science and Skiing IV. Maidenhead: Meyer & Meyer Sport (UK) Ltd.; 2009.

77. Meyer F. Biomechanical analysis of alpine skiers performing giant slalom turns [PhD-Thesis]: University of Lausanne; 2012.

78. Gilgien M, Spörri J, Kröll J, et al., editors. Speed an injury risk factor in competitive alpine ski racing? In: Abstract Book – 17th Annual Congress of the European College of Sport Science (ECSS); 2012; Bruges.

79. Kruger A, Edelmann-Nusser J. Application of a full body inertial measurement system in alpine skiing: a comparison with an optical video based system. *J Appl Biomech*. 2010;26(4):516-21.

80. Chardonnens J, Le Callennec B, Favre J, et al. Automatic measurement of key ski jumping phases and temporal events with a wearable system. *J Sports Sci*. 2012;30(1):53-61.

81. Muller E. Analysis of the biomechanical characteristics of different swinging techniques in alpine skiing. *J Sports Sci*. 1994;12(3):261-78. doi:10.1080/02640419408732172.

82. Scheiber P, Seifert J, Muller E. Relationships between biomechanics and physiology in older, recreational alpine skiers. *Scand J Med Sci Sports*. 2012;22(1):49-57. doi:10.1111/j.1600-0838.2010.01146.x.

83. Chardonnens J, Favre J, Le Callennec B, et al. Automatic measurement of key ski jumping phases and temporal events with a wearable system. *J Sports Sci*. 2012;30(1):53-61. doi:10.1080/02640414.2011.624538.

84. Drenk V. Photogrammetric evaluation procedures for pannable and tiltable cameras of varlable focal length. Conference Proceedings ISBS -12 International Symposium on Biomechanics in Sports; Budapest1994. p. 27-30. Retreived from: http://w4.ub.uni-konstanz.de/cpa/article/view/2440.

85. Drenk V. Panning - Zusatzprogramm zur Behandlung schwenk- und neigbarer und in ihrer Brennweite variierbarer Kameras in Peak. Software Documentation. Institut für angewandte Trainingswissenschaften, Universität Leipzig, 1993.

86. Regensburger K. Photogrammetrie - Anwendungen in Wissenschaft und Technik. Berlin: Verlag für Bauwesen; 1990.

87. de Leva P. Joint center longitudinal positions computed from a selected subset of Chandler's data. *J Biomech*. 1996;29(9):1231-3.

88. Luhmann T, Robson S, Kyle S, et al. Close range photogrammetry: principles, techniques, and applications. Dunbeath, UK: Whittles Publishing; 2006.

89. Abdel-Aziz YI, Karara HM, editors. Direct linear transformation from comparator coordinates into object space coordinates in close range photogrammetry. Proccedings of the American Society of Photogrammetry Symposium on Close-Range Photogrammetry; 1971; Falls Church: V.A: American Society of Photogrammetry.

90. Kwon YH. DLT-Method. http://www.kwon3d.com/theory/dlt/dlt.html. 1998 [accessed 12. November 2012].

91. Smith G. An iterative segment length normalization routine for use with linked segment models. In: Gregor RJ, Litsky AS, editors. Conference Proceedings of the18th Annual Meeting of the American Society of Biomechanics; Columbus, OH1994. p. 35-6.

92. Clauser CE, Mc Conville JT, Young JW. Weight, Volume and Centre of Mass Segments of the Human Body. AMRL TR69-70. Wright-Patterson Airforce Base,OH.1969.

93. Schiefermüller C, Lindinger S, Müller E. The skier's centre of gravity as a reference point in movement analyses for different designated systems. In: Müller E, Bacharach D, Klika R, Lindinger S, Schwameder H, editors. Science and Skiing III. Oxford: Meyer & Meyer Sport (UK), Ltd.; 2005. p. 172-85.

94. Chiari L, Della Croce U, Leardini A, et al. Human movement analysis using stereophotogrammetry. Part 2: instrumental errors. *Gait Posture*. 2005;21(2):197-211. doi:10.1016/j.gaitpost.2004.04.004.

95. Hatze H. The use of optimally regularized Fourier series for estimating higher-order derivatives of noisy biomechanical data. *Journal of Biomechanics*. 1981;14(1):13-8.