NORWEGIAN SCHOOL OF SPORT SCIENCES

Ivar Hereide Mannsåker

The effect of gate offset on skier mechanics in flat terrain for male and female elite skiers

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Abstract

Purpose: The purpose of this study was to investigate the effects increasing the offset of gates in giant slalom on injury risk of World Cup skiers. Injury risk factors has been used as surrogate parameters for injury risk.

Method: Data was collected in Kvitfjell during a training camp of the Norwegian national ski team. Three male and 2 female World Cup skiers participated in he study. An open rhythmic course was set by one of the coaches on a slope with an average incline of 13 degrees. The course had an average gate distance of 27.0m and an offset of 6.6m (Course 1)1. Two sections of 5 gates was then adjusted by increasing the offset by 1.0m (Course 2) and then by 1.5m (Course 3). Participants skied 3 runs in each course. Terrain and course-set were measured using dGNSS. Athletes carried a dGNSS and inertial navigation system from which speed, ground reaction force, turn radius and impulse (the ground reaction force over time) were calculated.

Results: In course 2 and 3, where offset was increased by 1.0m and 1.5m respectively compared to Course 1, speed was reduced. Each additional gate with increased offset led to and additional reduction in speed. In the first course intervention section the results were most homogenous. Here Course 2, where offset was increased by 1.0m, caused a speed reduction per turn with increased offset of about 0.6km/h compared to course 1. In course 3, where the offset was increased by 1.5m, the speed reduction was about 0.9 km/h for both sexes. Hence the course-set intervention had similar effects on women and men in absolute and relative terms. Increased gate offset in the flat terrain did not lead to any increase in maximal ground reaction forces or decrease in minimal turn radius. The impulse and physical load on the athletes was increased with increasing gate offset.

Conclusion: In flat terrain the main consequence of increased gate offset are speed reduction and an increased physical load. Minimal turn radius and maximal ground reaction force were not changed. Course-setters need to consider the trade-off between speed control and physical fatigue when setting courses in flat terrain.

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1. Introduction

This study is part of a larger project by the International Ski Federation. The aim of the project is to reduce injury risk through a better understanding of how course-set influences injury risk factor. Earlier in this project the course risk have been assessed, 3D course data have been gathered, and there have been conducted research on World Cup forerunners. This study fit into this project by conducting an experimental study on course-set. The project aims to present recommendations of how to set courses.

In this thesis the effects of course-set in giant slalom on world cup skiers have been investigated. Trajectories have been measured and force has been estimated to calculate a set of variables which has been compared with a set of parameters calculated from gate positions. Appendix 1 details the mathematics behind the definitions and calculations of the gate and skier parameters. Appendix 2 contains a prediction model combining the data from this study with the data from an earlier study on world cup skiers with the goal of predicting the skier parameters linked with increased injury risk.

This thesis is written as an article with an extended theory part. For method, results and discussion see the article.

2. Theory

2.1 Alpine skiing

Alpine skiing is a Winter Olympic sport which consists of four disciplines: Downhill (DH), Super-G (SG), Giant slalom (GS) and Slalom (SL). The competitions consists of races held on natural slopes with skiers passing a set number of gates to reach the finish in shortest time possible. Each discipline is defined through different terrain and course-set characteristics set by the governing body the International Ski Federation (FIS). These four disciplines are defined by their drop in vertical meters betyween start and finish. SL, GS and SG are also defined by the number of direction changes in a race, given as a percentage of the vertical drop the course has. The course-set for each run is set by a coach from one of the countries participating in the race. As the regulations set a range of allowed number of change of direction during the race, course-setters has some freedom to adapt their course to the snow and terrain conditions of the day and create the sport challenge he/she sees fit. However, as there is no regulation for the offset of the gates, or course-setting in specific terrain i.e. flat or steep terrain or terrain transitions, course-setters can set an almost infinite number of varying courses on the same slope.

The fact that course-setters have this freedom opens up the possibility for coaches to set courses that are more or less technical or with higher or lower speed. This freedom can be used to accommodate the characteristics of the slope or to accommodate the abilities of the skiers on the course-setters team. Having the course-setter on your own team is therefore seen as an advantage for the skiers of the course setters nation.

Course-setters generally rely on measuring the distance to the previous gate with a tape measure and from there, rely on experience where the gate should be placed to have a sportive challenge and save course (Gilgien et al., 2015, p. 15).

Hence, having recommendations and probably regulations considering the steepness of the slope in order to reduce the freedom of course-setters might increase the fairness of the competition and reduce the risk of injuries, but should also leave freedom to the course setters to set interesting courses.

As a result of the terrain and course-set characteristics of the different disciplines kinematics and kinetics are different between disciplines. DH and SG are characterized by high speed and long turns, and often grouped as the speed disciplines whereas GS and SL are characterized by sharper turns and lower speed and often grouped as the technical disciplines(Gilgien et al., 2015, p. 10). DH and SG competitions consist of a single run, while GS and SL consists of two runs in difference courses with the combined time of the two runs declaring the winner. In addition the equipment is different for the different disciplines. In addition to the course characteristics, the equipment is different between the disciplines. SL use short skis with a small sidecut radius. From GS through SG to DH the skies get longer with smaller sidecut radius. These difference skis have different characteristics, where the skies sued in SL increase the forces on the athletes and reduce the speed in turns(Josef Kröll et al., 2016, p. 29)

2.1.1 Giant Slalom

GS races are regulated to have between 250m-450m vertical drop for men and 250-400m for women in World Cup (WC) courses. For both sexes the course has to be set with the number of direction changes between 11%-15% of the vertical drop in meters (*ICR*, 2022, p. 97). GS WC races are on average 1437 meters long with a vertical drop of 407 meters and 51 direction changes. The gates has on average an offset of 7.47m and a vertical distance of 25.12 meters at an incline of 17.8 degrees (Gilgien et al., 2015, p. 10).

In a GS race the skiers are turning 92% of the run time. The turns have a cyclical pattern (Gilgien et al., 2015, p. 5). This causes a pronounced loading and unloading pattern in a cyclic movement from turn to turn. As a result of the sharpness of these turns, and the speed of the skiers, the impulse in each turn in GS is higher than in SG or DH, however as the race duration is longer in both SG and DH the total impulse experience is higher in these disciplines, when compared to a single GS run (Gilgien et al., 2018, p. 7).

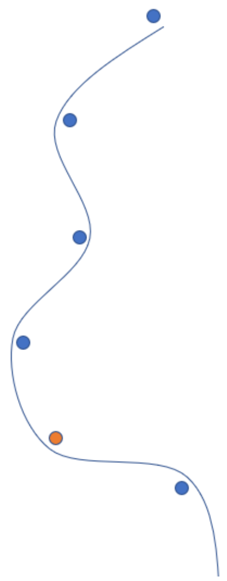

Figure I: Imagined course-set in GS, Blue dots are "normal" gates, orange dot is a delayed gate and blue line is imagined trajectory through gates

Gates can be set in two ways, ether as a "normal" gate, or as a delayed gate both depicted in Figure I. "Normal" gates are a single gate with turn transitions and change of direction between each gate. Delayed gates are a second gate on the same side as the previous, shortly after it. These gates are usually used to stretch out a turn. There are on average between two and three delayed gates in a course (Gilgien et al., 2015, p. 10). While delayed gates count as two different gates, they are only considered a single change of direction.

2.2 Injury Prevention

2.2.1 Van Mechelen's injury prevention method

Van Mechelen describes a method of conducting injury prevention research (Van Mechelen et al., 1992, p. 84). This method is widely used in injury prevention research. The method consists of a four step "sequence of prevention"(Van Mechelen et al., 1992, p. 84). These steps present a framework for measures to prevent sports injuries. The first step is to establish the epidemiology of the sport. The extent injuries consists of the incidence rate of injuries and the severities of injuries. Reducing ether will reduce the number of severe injuries.

The second step is to establish the aetiology and mechanism of injuries. The underlaying mechanism of injuries cannot be established without first understanding in which situations injuries occur therefore, this is important to measure. The mechanisms of why these situations are dangerous for athletes consists of understanding why these situations have a high risk of an injury occurring, the types of injuries occurring, and why the severity of the occurred injuries is higher than in other situations.

The third step is to introduce preventative measures based on the knowledge gained in step two. For preventative measures to be effective they must be designed to combat the specific mechanics established in the previous step.

The fourth step is to repeat step 1, with the goal to compare the results before and after the preventive measures were implemented. The effectiveness of the preventative measures are hence assessed by the difference in the epidemiologic data between step one and 4. As step four is identical in method as the first, it can function as the beginning of a new cycle of injury prevention. This relation highlights the importance of having recent data describing the epidemiology of the athletes of the sport. If other interventions were introduced between step one and four than the ones suggested in step three, the change in epidemiology cannot be attributed to these.

2.2.2 Epidemiology

Alpine skiers have a high risk of time-loss injuries when compared to other Olympic sports (Engebretsen et al., 2010, p. 777; Soligard et al., 2015, p. 442, 2019, p. 1087; Steffen et al., 2017, p. 31). Time-loss injuries are here defined as any injury that causes one or more days of absence from training or competition. During a season there are up to 35 time-loss injuries per 100 athletes (Haaland et al., 2016, p. 34; Hisdal & Bahr, 2019, p. 7). When adjusted for runtime, GS, SG and DH see a similar amount of time-loss injuries per hour skied, with 0.61 injuries per hour skied (Gilgien et al., 2014, p. 744). Most of these injuries occur during official WC activities with 45% of injuries occurring during WC competition, and 16.2% during official WC training runs. In addition 25.1% occur during regular ski training (Flørenes et al., 2012, p. 60).

The extent of injuries in alpine skiing has been recorded/documented since FIS developed their Injury Surveillance System (ISS) in 2006 (Spörri et al., 2017, p. 602). ISS documents injuries through retrospective interviews with athletes, coaches, and medical staff. As such the extent of incidence and severity of injuries in alpine skiing is well documented.

The most common injury type to occur is joint/ligament with 44.4 % of injuries with the most common body part being the knee with 36% of injuries (Flørenes et al., 2012, p. 62). The most common diagnosis being a rupture of the anterior cruciate ligament (ACL).

Most injuries (80%) happen during turning, while landing after jumps account for 19% of the injuries (Bere, Flørenes, et al., 2013, p. 669). Injuries to alpine skiers happen in both skiing and crash situation, where ACL rupture mostly happen during skiing and traumatic injuries happen during crash and fall situation (Bere, Mok, et al., 2013, p. 671; Spörri et al., 2017, p. 602). There are no studies describing the injury rate in specific turns, e.g. whether turns with large vertical distance has higher injury incidence than turns with less vertical distance. There are not reported any significant intersex differences in the epidemiology of GS skiers.

2.2.3 Etiology

Studying the mechanisms behind injury risk factors of alpine skiers are difficult as any study will have low statistical value since there is such a small cohort of elite skiers. As such very few factors have been statistically verified. As the risk factors are difficult to verify empirically the opinions of expert stakeholders is used to identify risk factors. Expert stakeholders have repeatedly ranked “fatigue” and “high speed” as high risk factors for skiers (Spörri et al., n.d., p. 32; Spörri, Kröll, Amesberger, et al., 2012, p. 605,607; Spörri et al., 2017, p. 1061). Spörri et al., 2017 compiled a rather extensive list of factors split into four categories: athlete-, course-, equipment-, and snow-related risk factors with related potential prevention measures. Of the athlete-related risk factors five of them are related to the course being technical or physically difficult: “Fatigue (within a course or training session)”, “Inappropriate tactical choices”, “Insufficient physical fitness”, “Technical mistakes” and “Insufficient core strength/core strength imbalance” (Spörri et al., 2017, p. 603). Of the course-related injury risk factors three are directly related to speed: “High skiing speed combined with terrain transitions”, “High skiing speed combined with small turn radius” and “High skiing speed in general”. The rest of the course-related injury risk factors are “Inappropriate jump construction”, “Inappropriate net positions”, “Limited spill zones” and “Poor visibility” (Spörri et al., 2017, p. 605). As of 2015 only four risk factors have been statistically verified. These four being: “Gender”, “High skill”, “Unfavourable genetics” and “Insufficient core strength / core strength imbalance” (Spörri et al., 2017, p. 606). Only two of these factors overlap with what we can adjust through course-set; “High skill” and “Insufficient core strength / core strength imbalance”.

The term fatigue is used as both the fatigue skiers experience “within a course or training session” (Spörri et al., 2017, p. 603), and the fatigue skiers experience as a result of “overloaded schedule and jetlag” (Spörri et al., n.d., p. 21). From this point “fatigue” is used for the fatigue experienced during races or training sessions unless directly expressed otherwise.

While many expert stakeholders name fatigue as a risk factor, a more accurate factor to use could be the athletes physical aspects as the fatigue experienced by the skier during the race is of less importance than the physical aspect of the skier at the start (Spörri et al., 2017, p. 609). The potential prevention measures to combat the athlete-related injury risk factors, centre around increasing the skill and physical abilities of the skiers (Spörri et al., n.d., p. 31, 2017, p. 609). Fatigue experienced from an overloaded schedule or jetlag can also be accommodated for within physical aspects so long as the fatigue incurred this way is similar for all the athletes competing.

High speed in general is seen as a major risk factor because of its factor in the kinetic energy of skiers. The kinetic energy of skiers is equal to $\mathrm{E} = 1/2\mathrm{m}v^2$. The kinetic energy is the energy dissipated in crash situations (Gilgien et al., 2014, p. 744). This applies to injuries occurring both in skiing and fall situations. From the formula for kinetic energy, we can see that the energy that needs to be dissipated increases exponentially with speed. High speed will also increase the maximum forces experienced by skiers in turns as the force experienced is related to the mass of the object and its acceleration. Higher speed or shorter turn radius should then result in higher ground reaction forces on the skiers. Whether this results in an increase in impulse though the turn is not obvious as the instantaneous forces increase, but the duration of the turn should reduce similarly.

High speed in courses can also change the timing of the turns for the skiers. With high speed, the course being the same, the timings for the turn should be shorter, i.e. the time from turn exit to initiation of next turn, time to gate passage and time to max ground reaction force. Faster timing between gates should give skiers less time to adapt to changing conditions and/or less time to adapt their line through the gate in reaction to a mistake. Faster timing in gates could then increase the risk of injury as mistakes can be easier to make, and harder to correct for.

The effect of high speed on injury risk factors is complex, having effect on several different aspects of injury risk factors. High speed increases both the risk of an injury situation and the severity of any eventual injury situation. There has not been suggested any negative effects of low speed on the injury risk of athletes. Exploring prevention methods which can reduce speed in specific areas of a course such as in terrain transitions, or in general could be an effective method of reducing the number of severe injuries in alpine skiing.

2.2.4 Preventive Methods

The third step in van Mechelen's method is to introduce preventative measures based on the aetiology established in step 2.

The potential prevention measures suggested against athlete-related injury risk factors centre around increasing the skill and physical aspects of skiers. Some elite skiers have reached a plateau from where improving is exponentially more difficult(Spörri et al., n.d., p. 21). Increasing their physical abilities could then be an ineffective method of reducing this injury risk. In addition, catering the course to the abilities of the most elite skiers could cause the competition to be dangerous for young skiers as their physical abilities are not to that level yet. Hence it might be more effective to achieve the same results by reducing the physical and technical requirements of the course through course-set. FIS then must adapt course-set to accommodate for the physical aspect of skiers and set courses which are not dangerous to compete in for the top 60 skiers

As high speed increases both the required physical aspects the course requires and the severity of any injuries that occurs, a major method of reducing the injury risk of athletes is to reduce the speed of skiers in the course. This can be achieved mainly through the equipment skiers are wearing, race-suit, boots, bindings or skis, or through course-set.

There has been suggested several changes to skier equipment in order to regulate their speed in races. These methods aim to increase the natural forces which resist the movement of the skiers: air resistance and ski-snow friction. Increasing the air resistance can be done through regulating the race-suits. Increasing the ski-snow friction can be done through changing the skis allowed to be used in competition (Gilgien et al., 2016, p. 10; Spörri, Kröll, Gilgien, et al., 2016, p. 17). The only preventative method statistically proven to reduce injury risk of skiers in alpine skiing is longer skis with less profile width (Spörri et al., 2017, p. 611).

In GS the loss of speed attributed to air resistance is low (Gilgien et al., 2018, p. 5). Change in athlete equipment like racing suit has a limited potential for increasing the air-resistance. Therefore, regulations on the equipment skiers wear aiming to increase the air resistance might have a low impact on the speed of skiers in GS as a result of the low effect of air resistance in general.

Increasing the offset and reducing the vertical distance of gates has been suggested as methods of controlling the injury risk of skiers (Gilgien et al., 2015, p. 16, 2020, p. 1046, 2021b, p. 4; Spörri, Kröll, Fasel, et al., 2016, p. 5; Spörri, Kröll, Schwameder, et al., 2012, p. 1076). The study by Gilgien et al. (2020) which includes 571 turns showed that only an increase in gate offset had an effect on speed of skiers in flat terrain, while both a decrease in vertical distance and increase of offset had an effect in moderate and steep terrain. The same study also showed that an increase in gate offset in all types of terrain could have adverse effects. Larger gate offset correlated with larger ground reaction forces (GRF_{MAX}) and total impulse throughout the turn. It also correlated with a reduction in the minimum radius ($Radius_{MIN}$) in the turn. A lack of in-depth knowledge of course-set and its effects on injury risk situations could cause course-setters to increase the offset or reduce the vertical distance of gates in the wrong situations and increase the risk of injury.

Course-set in male WC races has been shown to be dependent of the steepness of the slope. When steepness increases the gate offset increases slightly (-0.18 meters per degree of inclination) and that the gate distance slightly reduced as the steepness increased (0.11 meters per degree of inclination) (Gilgien et al., 2015, p. 14). Gate distance is highly correlated to vertical distance, but not to gate offset (Gilgien et al., 2020, p. 43). As such, the speed of skiers is currently being controlled by both vertical distance and offset of gates in WC races. The low change in vertical distance can be explained by course-setters constantly measuring the distance from the previous gate when setting a course (Gilgien et al., 2015, p. 15).

As discussed, reducing the speed on its own will increase the total impulse skiers experience. Course-set could however also increase the total impulse on skiers. As such reducing the speed through equipment might be necessary in order to reduce the physical aspects risk factor.

Gilgien et al. 2020 conducted the study on forerunners in 7 WC competitions within two consecutive seasons. The biomechanical variables were calculated for each turn using a differential Global Navigation Satellite System (dGNSS), this data was then imported into a mixed effect model. This design can explore the correlation between factors but can draw no conclusion of the causation. As this method looks at each individual turn in the study on each own, the study explores no possible compounding effects in consecutive turns.

As the Gilgien et al. 2020 study uses WC races over several seasons there will be a large number of uncontrolled variables, for example the snow conditions will vary between some courses being salted, some having artificial snow, and some having natural snow. The forerunners will vary each race, with each having different skill level and choose different lines through the gates, with none of them being current WC racers. The participant group is not current WC racers, but former WC or current Europa cup (EC) racers. Hence the participants are not part of the population the study generalizes towards.

The study by Spörri et al. (2016) found no change in GRF_{MAX} as a result of shorter offset of gates. The study did not measure speed and did not calculate $Radius_{MIN}$ or impulse. The study was conducted on 10 world class athletes, divided into 2 groups which skied GS or SL courses, doing 3 runs in two different set courses where 8 turns were analysed from each run. The GS was conducted with a course set by a national team coach aiming to represent the course-set in WC races. The first course had a 6 m offset in all the analysed turns and in the second course the offset was changed to 10m, with all other parameters staying the same. These distances were chosen as they correspond with the spectrum of turns seen in WC, i.e. the minimum and maximum values found in WC course-set. In total 240 GS turns were analysed.
Motion data was collected with 2 inertial measurement units one at the sternum and one at the sacrum, and force was recorded with pressure insoles in the shoes. Speed was not used as a parameter in the study as it was only investigating the forces on the back while skiing.

The subjects of the study were WC or EC level. However, there is no description of how many was WC, and which group they were placed in. The sex of the subjects is not mentioned. Hence, composition of the subject group is not described adequately to be able to generalize the results to greater population. The data collection method is lacking the accuracy and precision of modern collection methods but allows for analysing a larger number of turns fast.

The study by Spörri et al. (2012) found a of -0.32 m/s loss of speed in the turn as a result of a reduction in $Gate_{OFFSET}$ at the end of the turn. The study found no change in maximal ground reaction forces and did not report $Radius_{MIN}$. Spörri et al. (2012) did not calculate the impulse through the turn but notes that it might be higher as a result of the ground reaction forces being the same and the loading time being longer. The study was conducted with a single top world-class skier skiing 12 runs, in two different courses on the same slope. The course initially had 5 gates with a vertical distance of 26m and offset of 12m which was changed to 10m for the 6 last runs. The offset was chosen to represent each end of the spectrum of course-set in WC races. Data was collected with cameras. A 3D model of the skier was reconstructed based on manually digitizing each frame. Since this method uses a work heavy method only one single turn was analysed for each run.

This study compares a very small amount of turns (12) and has only one subject. The sex of the subject is never mentioned. The data collection method can produce accurate results but is exposed to error originating from the researcher as anatomical landmarks must manually be digitized in each frame. This method of data collection has low impact on the skier, as no equipment is fastened to the skier. As the number of turns analysed is low, the statistical power of the study is low. Using a single subject controls for unwanted variables but makes the result impossible to generalize to a larger population. As the study analyses few turns the results should not be considered conclusive for the greater population, but as a case study.

Combined the 2012 and 2016 study by Spörri et al. and the 2020 study by Gilgien et al. create the theoretical base for course-set as a preventative method for reducing the injury risk of in GS for WC athletes. These studies have proven course-set as an effective method of preventing injury risk in GS, however there the studies investigating this has significant limitations. These studies all use male skiers as subjects, and most are not current WC racers. The methods used are ether work-heavy and impossible to utilize for larger studies, or has low accuracy and precision. So far there is no study that has been able to confirm and generalize a causal relationship between course-set and injury risk of GS skiers. Hence the knowledge of the field consists of a correlation between $Gate_{OFFSET}$ and $Gate_{VERTICAL}$ and injury risk, and a case study of causation between $Gate_{OFFSET}$ injury risk. Further investigations aiming to extend the knowledge of the field should aim to establish the causal relationship between both $Gate_{VERTICAL}$ and $Gate_{OFFSET}$ and injury risk factors using study designs which allows for generalizing to both male and female skiers at both WC and EC level.

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Article

Abstract

Purpose: The purpose of this study was to investigate the effects increasing the offset of gates in giant slalom on injury risk of World Cup skiers. Injury risk factors has been used as surrogate parameters for injury risk. **Method:** Data was collected in Kvitfjell during a training camp of the Norwegian national ski team. Three male and 2 female World Cup skiers participated in the study. An open rhythmic course was set by one of the coaches on a slope with an average incline of 13 degrees. The course had an average gate distance of 27.0m and an offset of 6.6m (Course 1)1. Two sections of 5 gates was then adjusted by increasing the offset by 1.0m (Course 2) and then by 1.5m (Course 3). Participants skied 3 runs in each course. Terrain and course-set were measured using dGNSS. Athletes carried a dGNSS and inertial navigation system from which speed, ground reaction force, turn radius and impulse (the ground reaction force over time) were calculated. **Results:** In course 2 and 3, where offset was increased by 1.0m and 1.5m respectively compared to Course 1, speed was reduced. Each additional gate with increased offset led to and additional reduction in speed. In the first course intervention section the results were most homogenous. Here Course 2, where offset was increased by 1.0m, caused a speed reduction per turn with increased offset of about 0.6km/h compared to course 1. In course 3, where the offset was increased by 1.5m, the speed reduction was about 0.9 km/h for both sexes. Hence the course-set intervention had similar effects on women and men in absolute and relative terms. Increased gate offset in the flat terrain did not lead to any increase in maximal ground reaction forces or decrease in minimal turn radius. The impulse and physical load on the athletes was increased with increasing gate offset. **Conclusion:** In flat terrain the main consequence of increased gate offset are speed reduction and an increased physical load. Minimal turn radius and maximal ground reaction force were not changed. Course-setters need to consider the trade-off between speed control and physical fatigue when setting courses in flat terrain.

Introduction

In World cup (WC) competitive alpine skiing, the risk of injury is relatively high compared to other Olympic winter sports [1,2]. While injuries in giant slalom (GS) were found to be primarily linked to the mechanics of turning (i.e. high speeds, small turn radius, large ground reaction forces and high impulse), injuries in downhill and super-G were more associated with speed and impacts [3]. Expert stakeholders such as coaches and other key practitioners see course-set as primary measure to reduce injury risk. [4,5] Biomechanical research in the field has shown that course-set manipulations are suitable to reduce injury risk factors such as speed, forces, turn radius, inward lean etc [6]. During the seasons 2010 – 12 the effect of course-set and terrain on injury risk factors was assessed on men's World Cup races, including >500 GS turn and ~200 super-G turns [7–9]. Based on these data a model was developed to predict injury risk factors such as forces, turn radius and impulse for a given terrain incline, course-set (gate- offset and distance) and entrance speed. This model has never been assessed in an experimental setup, where the effect of course adjustments can be studied in a controlled manner and over a series of consecutive turns. Also, over the past decade several adjustments in equipment have been undertaken and course-set, snow surface preparation and the athletes' abilities, might have changed. It is indicated to establish an updated model that will allow to assess how course-set and terrain affect injury risk factors and facilitate this knowledge to set attractive but safe courses. The existing investigations on course-set only included male World Cup skiers. To assess how course-set and terrain influence injury risk factors and to establish course-set recommendations and regulations also for female skiers, female athletes need to be included in future investigations. Therefore, the aim of this study is to assess how course-set manipulations affect the skiing and injury risk factors for male and female World Cup skiers in flat terrain.

Methods

Protocol

Data collection was conducted in Kvitfjell, Norway during one day in April 2022on a slope with an average incline of 13.1˚ ± 3.3 ˚ during a GS race simulation session. Members of the Norwegian Alpine Ski Team (two female WC and three male WC skiers) were participating in the study. Snow was non-salted, compact and homogenous snow. The first three runs were skied in an open rhythmic course with an average gate distance of 27.0m ± 2.4m and an offset of 6.6m ± 0.9m (course 1). Between run 3 and 4, the course was adjusted in two sections (intervention section 1 and intervention section 2) where in each section three consecutive left turn gates (blue gates in Figure 1) were moved to increase the offset by 1.0m compared to the original course (Course 2). Between run 6 and 7, the same blue gates in the two intervention sections were moved to increase the offset with an additional 0.5m compared to run 4-6 (named “course 3”) and were skied for run 7-9. Each athlete skied in total nine runs in a course that was set by a WC coach.

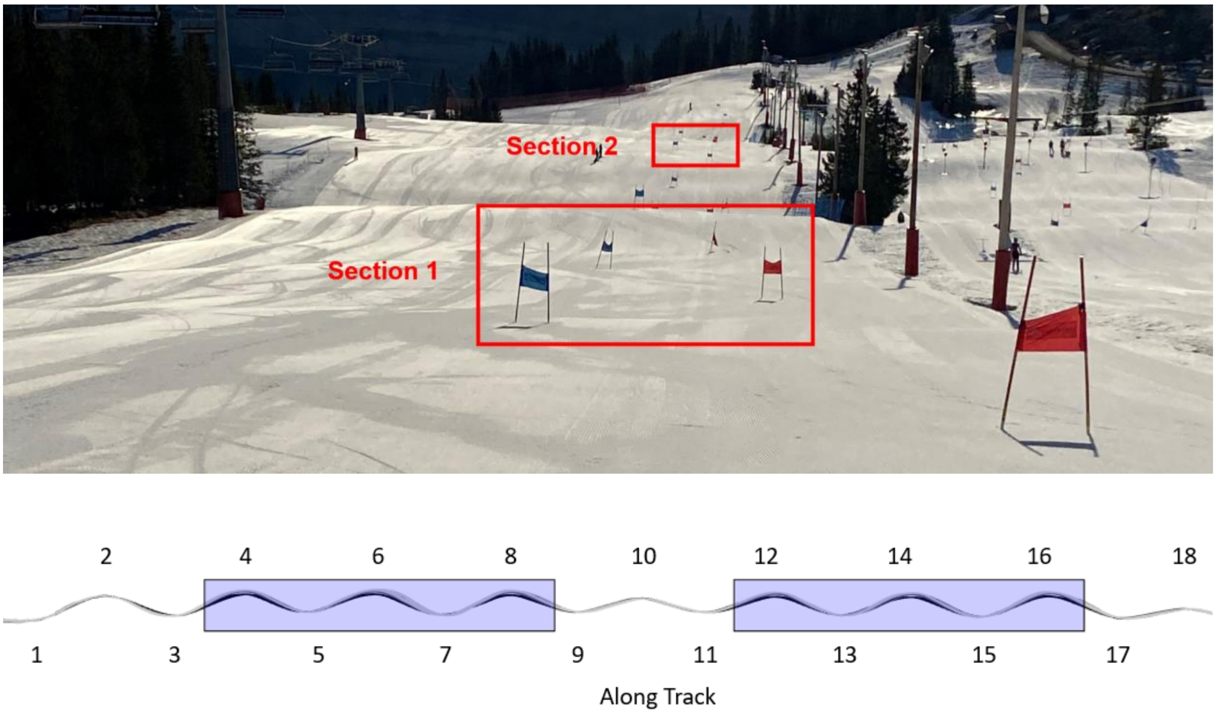

*Figure1: **a**) Image of the experimental setup with the original course-set (course 1). The two intervention sections in course 2 and 3 in which the gate offset was increased are highlighted in red. For the interventions the blue gates in the intervention sections were moved to the left by 1.0m (course 2) and 1.5m (course 3) compared to the original course 1while the red gates remained unchanged. **b**) Birds-eye view of the course with*

turns numbered and intervention sections marked with blue boxes. Skier trajectories are coloured with black for course 1, dark grey for course 2 and light grey for course 3.

Data collection methodology

Skiers carried a inertial navigation system (INS), (AsteRx i – S, Septentrio, Leuven, Belgium) that consisted of two differential global navigation satellite system (dGNSS) and an inertial measurement unit with two GNSS antennas (TW7972, Tallysman, Ontario, Canada) spaced by 35cm on the back protector and below the racing suit, which collected multi frequency and multi constellation GNSS raw data at 50Hz and inertial raw data at 200Hz (as shown in Figure 2). The gate positions and terrain surface were measured using dGNSS with rover antenna (GrAnt-G3T, Javad, San Jose, CA, USA) and receiver (alpha-G3T, Javad, San Jose, CA, USA). A GNSS base station (Altus NR3, Septentrio, Leuven, Belgium) was positioned less that one 1km from the slope and logged GNSS raw data at 50Hz for dGNSS post processing both for the skiers and the gates and terrain measures. All runs were filmed from three camera positions.

Geodetic processing

A tightly coupled INS solution was processed from the INS raw data (GNSS and IMU) carried by the skiers and from the GNSS raw data from the base station, post-processed using Terrapos (Terratec AS, Oslo, Norway) post processing software and time, position and inertia data were output at 50hz. The gate and terrain positions were calculated using dGNSS post processing software (Justin, Javad, San Jose, CA, USA). The Oregon of the IMU in the INS that was positioned approximately above TH6 was used as a representation of the skier as a point mass and was filtered using cubic spline functions prior to skier parameter calculation [10].

Figure 2: A male and female athlete wearing the measurement equipment below the racing suit on their back protector.

Course set and terrain characteristics

To present the snow surface, the surveyed point cloud was triangulated using the Delaunay method and gridded on a rectangular grid to a digital terrain model. The incline of the local terrain was geometrically derived from the local terrain surface normal vectors, then averaged for the area of each turn and expresses as the angle to the horizontal plane, called $\text{Terrain}_{\text{INCLINE}}$ [7].Course-set was described by the independent components gate offset ($\text{Gate}_{\text{OFFSET}}$, which in other studies is also called the horizontal gate distance), the vertical gate distance ($\text{Gate}_{\text{VERTICAL}}$) and the linear gate distance (figure 3). The distance calculations followed the definition in previous studies [8,9].

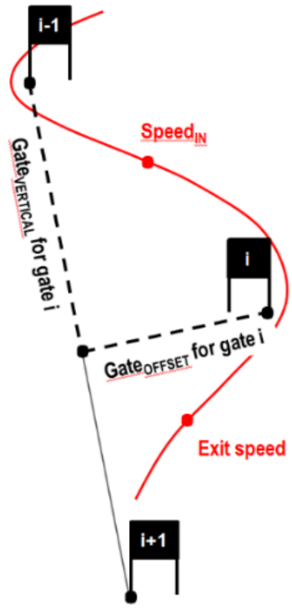

Figure 3) Illustration of the vertical gate distance ($\text{Gate}_{\text{VERITCAL}}$), the gate offset $\text{Gate}_{\text{OFFSET}}$*) and the deflection points marking turn start and end where the speed into the turn and turn exit speed were measured.*

Calculation of skier mechanics

Continuous data for ground reaction and breaking force, impulse, turn radius and speed were calculated from the spline filtered position data according to the methods described earlier [3,8,9]. Turn start and end were defined as the deflection points of the trajectory between two turns [3,8,9]. Gate-to-gate times were calculated from the time points the skier trajectory passed the gate. Turn initiation was defined as the point where the skiers had a radius of less than 30m. Minimal turn radius ($Radius_{MIN}$) was determined as the smallest radius in the turn, and maximal ground reaction force (GRF_{MAX}) was calculated as the largest ground reaction force in a turn. Entrance speed ($Speed_{IN}$) into a turn was defined as the instantaneous speed at turn start and exit speed was defined as the instantaneous speed at turn end (figure 3). The change in speed during the turn (ΔSpeed) was computed as exit speed minus $Speed_{IN}$. Impulse as a measure of physical load on skiers was calculated as the time integration of the sum of air drag and ground reaction force from turn start to turn end, expressed as body weight over turn time (BWs). The calculations and mathematical definitions of the skier and gate parameters is detailed in appendix 1.

A virtual plane method was applied [11] to line up the data of all skiers at each 30cm along an average trajectory through the course. This approach allowed comparison of the data of all skiers spatially and in relation to gate passage, turn initiation, and turn start and end. For each skier the continuous mechanical data was averaged across all runs in a given course. The within – athlete differences for the continuous and per turn data for a given course were averaged (mean and SD) across all skiers of the same gender. The differences in skiing parameters between women and men and courses were conducted using the same virtual plane location approach for the continuous data and the per turn data.

Statistical Analysis

The data was divided into 6 groups (3 courses and 2 sexes). The mean and standard deviation for each variable was calculated per turn. One outlier in speed though the turn was identified through grubb's test in MATLAB and was removed. Two-way ANOVA test in JAMOVI (Jamovi 2.3, The Jamovi Project) were conducted to test between group differences. This was conducted individually for each parameter. Only differences between course 1 and 2, and between course 1 and 3 within sex was considered relevant and used in further analysis. A Bonferroni post-hoc test for correlation was used. Alpha level was set to *α= 0.05*.

Results

The effect of increased gate offset on speed.

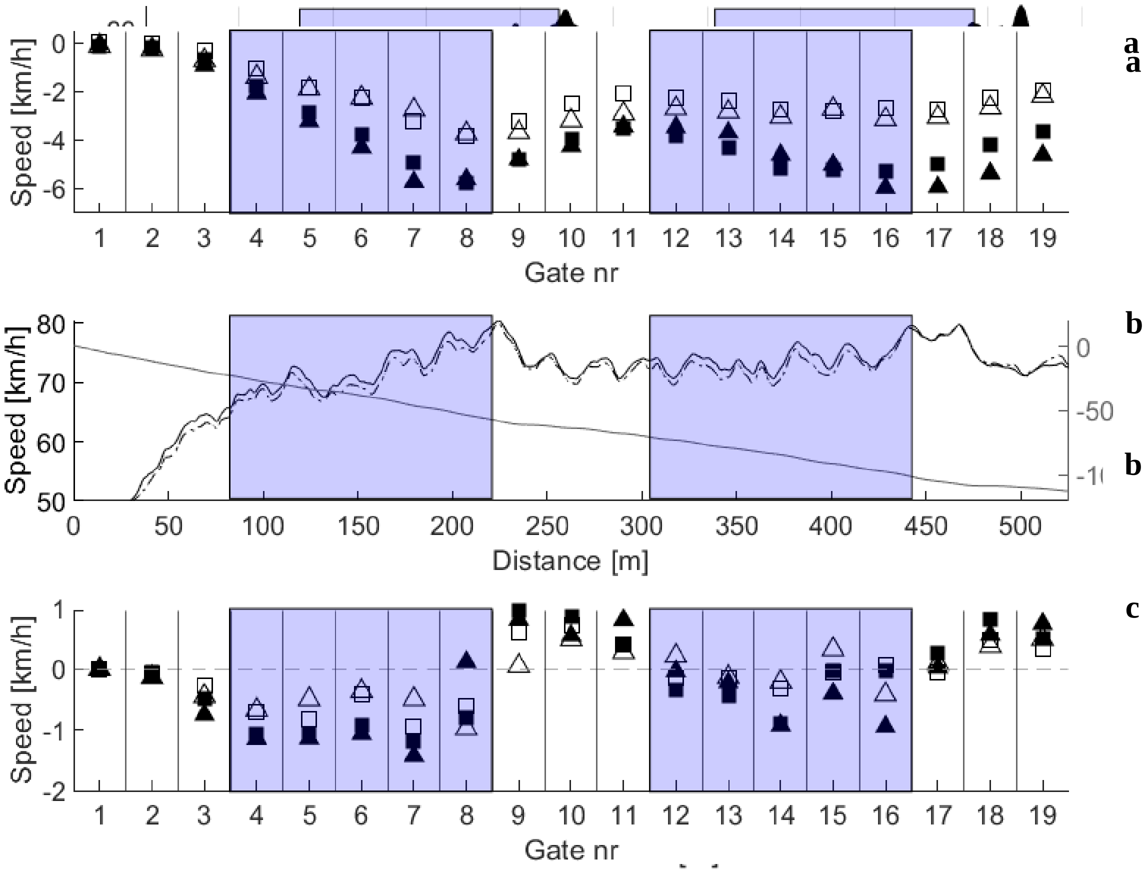

*Figure 5:**(a)** Relative speed from course 1. △ = female skiers course 2, ▲ = female skiers course 3, □ = male skiers course 2 and ■ = male skiers course 3. Intervention areas marked with blue boxes. **(b)** Average speed in original course and change in elevation through the course. Line = male skiers, dashed line = female skiers. Horizontal axis: distance along the mean trajectory from start. **(c)** ΔSpeed per turn compared to the ΔSpeed of course 1. △ = female skiers course 2, ▲ = female skiers course 3, □ = male skiers course 2 and = male skiers course 3. Intervention areas marked with blue boxes*

Figure 4 illustrates the development of the velocity of skiers though each course. It shows that speed was 65 km/h and higher when the course-set intervention started for intervention section 1. Speed increased throughout the first section of the course-set intervention but stalled at approximately 80km/h and fell to approximately 75 km/h in the transition between the two course-set intervention sections and increased again at the end of the second course-set intervention section. A slight reduction in speed is observable for course 2 and 3 from the first intervention section.

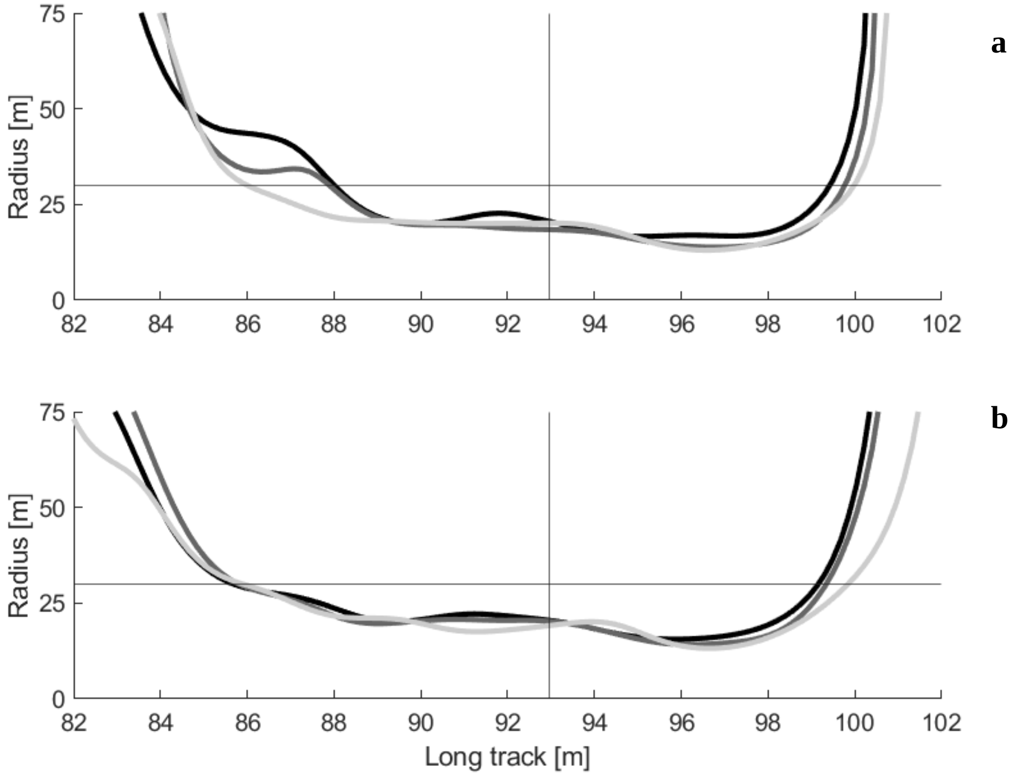

Figure 6: Turn Radius$_{MIN}$ (mean) for course 1, 2 and 3 for men ***(a)*** *and women* ***(b)*** *in turn 4 from the course intervention section 1, where the course was adjusted between course 1, 2 and 3. Course 1 is coloured in black, course 2 is coloured in dark grey and course 3 where the offset was increased by1.5m compared to course 1 is coloured in light grey. The horizontal line indicates the 30m turn radius, and the vertical line indicates the position of the gate.*

Figure 5 section (a) shows the speed in each turn for both sexes in course 2 and 3 compared to the speed in course 1 The change in speed was significant at the 0.01 level from turn 4 and through the rest of the course. Section (b) shows the vertical profile of the course and the speed of each sex in the original course. Section (c) shows the ΔSpeed in each turn for both sexes in course 2 and 3 compared to the ΔSpeed of course 1 in the same gate. Male and female skiers lost 0.6 km/h per turn in in course 2 and 0.9

km/h per turn in course 3 for the first intervention section. In the second section male and female skiers lost 0.1km/h per turn in course 2 and 0.4km/h per turn in course 3. The loss of speed had higher variability in the second intervention area compared to the first. There was identified no significant intersex differences.

The effect of increased gate offset on ground reaction force, radius, and impulse.

GRF_{MAX} in turns did not increase with the course-set intervention in any turn. $Radius_{MIN}$ only changed in turn 4. Figure 6 illustrates the overlap of the turn radius of the three courses in turn 4. Turn 4 was the only turn where with a statistically significant reduction in radius between the courses. The impulse per turn increased with the course intervention by 9.2% and 13.8% for male skiers and 8.5% and 13.1% for female skiers in course 2 and 3 respectively. The impulse did not differentiate in turn 10, which was the only turn identical in all courses after the first intervention.

The timing of the skiers in each turn also changed. The time from turn start to turn end, to gate passage, to GRF_{MAX} and to turn initiation all increased for both sexes in both intervention courses after the first intervention turn. For male skiers the time in turn increased by 0.07s (course 2) and 0.12s (course 3), time to gate increased by 0.04s and 0.08s, time to GRF_{MAX} increased by 0.05s and 0.08s and time to radius<30m increased by 0.02s and 0.03. For female skiers the time in turn increase by 0.08s (course 2) and 0.13s (course 3), time to gate increased by 0.04s and 0.08s, time to GRF_{MAX} increased by 0.06s and 0.06s and time to radius<30m increased by 0.02s and 0.03s.

Inter sex differences

The difference in change in speed from course 1 to course 2 and from course 1 to course 3 between male and female skiers was statistically equal in both relative and absolute terms. No significant changes in GRF_{MAX}, $Radius_{MIN}$ or impulse were identified.

Athlete perspective

The interviews with the skiers who skied during the experiment revealed that the courses were perceived as being suitable to ski consistent over the nine runs. The largest change the increased offset caused was that it increased the physical load. This corresponds well with the results from the technical data.

Discussion

The main findings of this study were: 1. Increasing the $Gate_{OFFSET}$ in GS reduced the speed of both male and female WC skiers in flat terrain. 2. Increasing the offset of gates in GS had no effect on GRF_{MAX}. 3. while $Radius_{MIN}$ only saw a significant change in the first turn with increased offset. 4. Increasing the offset of gates in GS increased the impulse of both male and female WC skiers in flat terrain.

This study was conducted to investigate the effects of increasing the offset of gates in GS on established parameters linked to injury risk. Five WC skiers, 2 women and 3 men, skied a course consisting of 20 gates in which two sections of 5 gates separated by 3 gates was adjusted by increasing offset. This was done twice creating three different courses in total, one with 1 meter increased offset and one with 1.5 meters increased offset. Each athlete skied these courses 3 times each. The results show that the skiers had significantly less speed in the courses with increased offset. $Gate_{VERTICAL}$ and inclination were not included as predictors as these variables were homogenous through all courses. The speed was significantly reduced from the first intervention gate and through the rest of the course. GRF_{MAX} was not changed, $Radius_{MIN}$ had a significant change in the first intervention turn, but not in subsequent turns. Impulse increased in all turns in which the offset was increased.

In the first intervention section, male and female participants lost 0.6 km/h in Course 2 and 0.9 km/h in Course 3 compared to Course 1. The braking effect was consistent in the first intervention section for both males and female skiers in Course 2 and 3, however, women in Course 3 experienced a smaller braking effect in the last gate in the first section. This was not large enough to change the overall statistical effect for the female athletes in the first intervention. Skiers gained speed in the turns separating the intervention sections when compared to the speed in Course 1. They did not regain all the speed lost in the first intervention section. The skiers in Course 2 and 3 entered the second section with less speed than in Course 1. The effect in the second section had larger variability. In this section, no sex in either course had speed loss in every turn compared to Course 1. The skiers probably did not reach a speed barrier in the first intervention in Course 1 as the speed increased through the section[12,13], while $Gate_{OFFSET}$, $Gate_{VERTICAL}$, inclination and snow conditions were the same for the gates. The skiers might have reached this speed barrier in the second intervention section as the speed remained consistent through the section in Course 1 while the parameters remained similar for all the gates. The data in the first intervention section shows that the braking effect compounds through several turns with a similar magnitude for each turn for both 1m and 1.5m offset. In this section, the braking effect is also linearly proportional to the increase in offset. However, that does not prove there is a linear correlation between increasing $Gate_{OFFSET}$ and reducing the speed of skiers within or outside this range. The change in braking effect and variation in loss of speed in the second intervention section could be explained by the skiers not reaching the speed barrier in the first section and possibly reaching a limit of the braking effect in the second section or the speed barrier of Course 2 and 3. While there were some slight differences between male and female skiers in some parameters in select turns, there were identified no statistically significant differences in ΔSpeed when compared over a whole intervention section in both speed relative to Course 1 and absolute speed loss.

The timings in turns were significant different in Course 2 and Course 3 when compared to Course 1 in both intervention section. Some of the slower timings in Course 2 and three can be explained by the lower speed and slightly longer linear distance between gates. Increasing the $Gate_{OFFSET}$ has been shown to increase the fraction of the turn cycle spent turning[6]. This effect could explain why the time in turns increases by more than three times the time to radius<30m. As the time to gate and time to GRF_{MAX} increases similarly the position of GRF_{MAX} in relation to gate should remain unchanged with an increase in $Gate_{OFFSET}$. As the timings for the turns are slower the turns could technically be easier for skiers to complete as they have more time to react and adjust to changing conditions and errors they make themselves. There was a slight difference between men and women in the timings, however these differences are too small to be significant in this study.

GRF_{MAX} saw no significant change as a result of the increase in $Gate_{OFFSET}$. This might be attributed to skiers not reaching the speed barrier in the first intervention section and hence turn mechanics might have yet to reach their maxima. As the skiers might not have reached this barrier the need to dissipate speed is not present[12]. This dissipation of speed could increase the GRF_{MAX} in turns[12]. While the GRF_{MAX} did not increase the impulse increased in both intervention sections. This could be a result of the GRF_{MAX} remaining the same but timings in turns increasing. These two effects together could show that the skiers experience the same load, but for a greater duration, which would increase the impulse in each turn.

$Radius_{MIN}$ was significantly smaller in the first turn of the first intervention for both male and female skiers. For the rest of the turns, there was a slight tendency for smaller $Radius_{MIN}$, but none of these was significant. The lack of significant changes to $Radius_{MIN}$ could also be explained by skiers not reaching the speed barrier, hence not needing to dissipate speed through the turns to be able to complete the course.

The results of this study are in accordance with the findings of earlier studies, where an increase in $Gate_{OFFSET}$ in flat terrain for WC alpine skiers also caused a reduction in speed and an increase in impulse[5,6,8]. However, while most of these studies predicted an increase in GRF_{MAX} and a reduction in $Radius_{MIN}$ our data did not indicate the same change. In our study, the participants had three gates before entering the first intervention section and might not have reach the speed barrier, also indicated by the gaining of speed through the section. Earlier studies that predicted this change in GRF_{MAX} and $Radius_{MIN}$ had a longer section to gain speed before entering the gates in which data was collected. As such, these studies might have reached the barrier before collecting the data. Earlier studies showing the same results on ΔSpeed and impulse were conducted on different levels of skiers, EC or former WC racers. Having current WC racers exhibit the same results indicates that the results can be generalized to most elite alpine skiers. These other studies have used other variables in addition to the $Gate_{OFFSET}$ into account to predict ΔSpeed, impulse and $Radius_{MIN}$. These variables were not included in this study as predictors for these parameters, as the variables were homogenous throughout the courses. Earlier studies have investigated the effect of course-set in different inclinations. The effects of how course-set changes in differing inclinations are not fully understood and needs to be further investigated.

While increasing $Gate_{OFFSET}$ results in a reduction in speed, there are negative effects of this method. While the existence of these effects are apparent, the balance between positive and negative effects are not understood. Reducing the speed in a dangerous situation could be completed through increasing the $Gate_{OFFSET}$, the negative effects if increasing the impulse or reducing the $Radius_{MIN}$ will also be introduced. An increase in impulse would increase the total load on athletes during the race. Hence in races with a larger load, either through a long course, or many high-load turns, increasing $Gate_{OFFSET}$ might be problematic since wrong implementations could increase injury risk factors. Implementing this method in turns with already heavy loading could also increase the injury risk factors rather than reducing them.

This study did not investigate the effects of reducing the $Gate_{VERTICAL}$ to reduce injury risk factors. Reducing the vertical distance of gates has been suggested as an effective method with little drawbacks[8,14]. This method has previously been shown to be effective in steep and moderate terrain to not increase impulse and GRF_{MAX} and to not reduce $Radius_{MIN}$. Increasing the $Gate_{VERTICAL}$ has, however, yet to be shown to be effective in flat terrain. Hence, showing this method as effective in flat terrain could increase the toolset of course-setters for reducing the injury risk in WC. This study did not investigate this method in order to be able to focus on $Gate_{OFFSET}$ as this has more theoretical backing in flat terrain.

Clinical implication

Our study shows that increasing the $Gate_{OFFSET}$ in WC GS skiing is an effective method for reducing speed. The study shows that both 1m and 1.5m increase in offset significantly affect speed and that the effect increases linear between these values. The effect of gate offset on speed is similar between male and female skiers in absolute and relative terms. As this effect compounds through multiple turns and is retained through some turns after the intervention, this method could be implemented through several different methods. The gates in the section where a lower speed is wanted could be moved to increase the offset. However, this might not always be possible owing to slope constraints such as a narrow slope where the rest of the slope must be used for safety nets. In such a situation, this study shows that the gates preceding this section could be moved and the resulting loss of speed would last several gates after. Since increasing the $Gate_{OFFSET}$ also increases the impulse which might increase the fatigue of skiers, the situations when the benefits of a reduction in speed outweighs the downsides of larges impulses, must be understood before implementation.

These results combined with the results[15] from earlier studies could be used for predicting the exit speed, GRF_{MAX} impulse and $radius_{MIN}$ of skiers based on the course geometry and the entry speed in turns. See appendix 2 for details of such a model. Use of such models could be used to predict the parameters linked with injury risk of athletes in courses before a world cup race. Use of such models in preparing and adapting World cup courses could result in reduced injuries of athletes.

Limitations

The method used in this study presents five limitations. The study was conducted on salted spring snow. Therefore, the snow conditions were slightly softer than the snow normally found in WC races. The data collection method provides no data for the ski-snow interaction. Hence we can’t discus the mechanisms of the braking effect. This knowledge could help explain the balance between the positive and negative effects of the intervention. The subject group is small at 5 participants. The data collection method provides no direct data of forces. This data had to be estimated through models based on dGNSS trajectories and IMU data. This method introduces some slight error to the force data, and dampening effect as the body functions as a spring from the ground to the back. The course did not allow for skiers to reach the speed barrier before data collection are. As the skiers might not have reached this barrier the mechanisms of the turns might not have been the same as would be seen in WC races.

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Definitions

dGNSS	Differential Global Navigation Satellite System.
DH	Downhill, discipline in alpine skiing.
FIS	Fédération Internationale de Ski, international governing body of alpine skiing.
$Gate_{OFFSET}$	Component of distance between gates that is normal to the direction of skiing.
$Gate_{VERTICAL}$	Component of distance between gates that is parallel to the direction of skiing.
GRF_{MAX}	Maximal Ground Reaction Force measured in a given turn.
GS	Giant Slalom, discipline in alpine skiing.
$Radius_{MIN}$	Minimal Radius of trajectory measured in a given turn.
SG	Super-G, discipline in alpine skiing.
SL	Slalom, discipline in alpine skiing.
ΔSpeed	Change in speed through a turn. Speed at exit of turn minus speed at entry.
WC	WorldCup, highest level of seasonal competition in alpine skiing.

Appendix 1 – Calculating skier and gate mechanics in Giant Slalom

Summary

Method for calculating skier mechanics from the trajectory of skiers and the position of gates. These positions must be expressed in $[x,y,z]$. This appendix was written in order to precisely describe the variables used in studying gate geometry and skier parameters in Giant Slalom. This was done because there are not good resources for accurate and mathematical expressions of these variables.

1 Gate variables

Gate positions are given in the form of $g_i = [x_i, y_i, z_i]$, where x and y is the local or geodetic position of the gate in meters and z is the altitude of the gate in meters.

1.1 Gate vectors

The vector $\vec{a}$ is given as the vectors from gate $i-1$ to gate i. The vector $\vec{b_i}$ is given as the vector from gate $i-1$ to gate $i+1$. These vector as given as

$$\begin{aligned} \vec{a_i} &= [x_i, y_i, z_i] - [x_{i-1}, y_{i-1}, z_{i-1}] \\ \vec{b_i} &= [x_{i+1}, y_{i+1}, z_{i+1}] - [x_{i-1}, y_{i-1}, z_{i-1}]. \end{aligned} \tag{1.1}$$

1.2 Gate to gate distance

The gate to gate distance is defined as the length of the vector $\vec{a_i}$. Hence gate to gate distance $= |\vec{a_i}|$

1.3 Gate Vertical

The vertical distance of gates is defined as the length of the vector component of $\vec{a_i}$ along $\vec{b_i}$. The projection of $\vec{a_i}$ along $\vec{b_i}$ is given as

$$\vec{v} = proj_b\mathbf{a} = \frac{b \cdot a}{|b|} b. \tag{1.2}$$

Hence the offset is then defined as Offset $= |\vec{v}|$

1.4 Gate Offset

The offset (O) of gates was defined as the length of the component of the vector v that is orthogonal to the vector $\vec{u}$

$$O = |\vec{a} - \vec{v}|. \tag{1.3}$$

1.5 Inclination

Inclination was defined as the angle between vector $\vec{a}$ and the z-plane. The z-plane was defined by the unit vector $[0,0,1]$ and the point $[0,0,0]$ The angle between two lines is given as

$$\theta = cos^{-1}(\frac{u \cdot w}{|u||w|}). \tag{1.4}$$

Using equation (1.2), (1.3) and (1.4), the inclination at the i-th gate becomes

$$\theta_i = cos^{-1}(\frac{\vec{a} \cdot (\vec{a} - proj_z\mathbf{a})}{|\vec{a}||(\vec{a} - proj_z\mathbf{a})|}), \tag{1.5}$$

where $proj_z\mathbf{a}$ is the projection of $\vec{a}$ along the unit vector of the z-plane.

2 Skier parameters

Points along the trajectory of skiers at position i is denoted as t_i.

2.1 Radius

The radius of each point on the trajectory was defined as the distance from t_i to the center of the circle which t_{i-1}, t_i and t_{i+1} lay. This was estimated through projecting the positions on the z-plane. The radius was calculated by creating lines normal on the vectors from the point t_{i-1} to i, and t_i to t_{i+1} given as

$$\begin{aligned} p_1 &= \frac{t_{i-1} + t_i}{2}, \\ p_2 &= \frac{t_i + t_{i+1}}{2}, \\ r_1 &= (t_i - t_{i-1}) \cdot M, \\ r_2 &= (t_{i+1} - t_i) \cdot M, \end{aligned} \tag{2.1}$$

where r describe lines origination in p which pass through the center of the circle and M is the rotational matrix defined as $\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

The intersection of these lines describe the center of the circle, and is calculated as

$$p_1 + k \cdot r_1 = p_2 + n \cdot r_2 \tag{2.2}$$

Split into two equations and solve for n and k in

$$\begin{aligned} n &= \frac{p_2 - p_1 + k \cdot r_2}{r_1} \\ k &= \frac{p_1 - p_2 + n \cdot r_1}{r_2}. \end{aligned} \tag{2.3}$$

Combining equation 2.2 and 2.3 returns coordinates of the intersection. The radius of the point t_i is then defined as the length of the vector from t_i and to the intersection.

2.2 Force

The force was calculated using the inverse pendulum method from Gilgien et al [1].

2.3 Turn transitions

As each skier their transition between each gate was defined the point between gates with the highest radius. The transition point between each gate was defined as the median position of the transition of each skier.

2.4 Speed

The speed at point t_i was defined as the change in position from t_{t-1} to t_i divided by the change in time T at the same points T_i and T_{i-1},

$$\frac{t_i - t_{i-1}}{T_i - T_{i-1}}. \tag{2.4}$$

The entry speed of a given turn is defined as the speed at the first transition point before the turn in question. The exit speed of a given turn is defined as the speed at the trajectory point immediately before the first transition point after the gate.

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Appendix 2 - Modelling skier parameters in Giant Slalom

1. Introduction

In order to test the results from the Kvitfjell study its dataset were combined with the dataset from a previous article in order to create a model. The goal of the model was to predict the skier parameters speed, GRF_{max} impulse and $radius_{MIN}$ in a given turn. This was done in order to test whether the data from Kvitfjell corresponds well with data from real world cup races, and if it is possible to predict the skier parameters speed, GRF_{max}, impulse and $radius_{MIN}$ per turn in world cup races. A model for predicting these parameters has its own value in that it can be used to predict the risk associated with turns withing a World Cup course.

2. Method

The model was based on data collected in the Kvitfjell intervention study and from forerunners in the 2010/12 seasons (Gilgien et al., 2015). The method for collecting the Kvitfjell data is descried in detail in the main article, and the method of the data from the World Cup forerunners in its article (Gilgien et al., 2015). Exit speed, GRF_{max}, impulse and $radius_{MIN}$ was chosen as dependent variables. These variables were chosen as they correlated with the risk of injury of skiers. The dataset containing the world cup courses did not contain tags for whether gates were delayed or not. All the gates were included for this model. The course variables gate distance, $gate_{OFFSET}$ and steepness, from the World Cup dataset were already calculated. The raw gate positions were not available in order to do the calculations the exact same way as in the Kvitfjell dataset. Hence, there might be some slight discrepancies in how the variables in the two datasets was calculated. The skiers and course parameters from the Kvitfjell dataset were calculated and combined with the dataset from the world cup into a larger dataset in MATLAB which was imported into Python. Kvitfjell dataset contains 369 turns, and the World Cup dataset contains 570 turns for a combined dataset containing 939 turns. The dataset contains data from world cup skiers in a training course set up for an intervention study and forerunner (former world cup skiers and current Europa cup skiers). Hence, there are no turns from current world cup skiers in a world cup course. The data set was randomly split into a training and a test set with 80% being designated to the training set and the remaining 20% to the test set.

The independent variables chosen was entry speed, $gate_{OFFSET}$, linear gate distance, steepness and sex of the skiers. These variables were chosen as they have been shown to be correlated to the dependent variables. The course variables are explained in detail in appendix 1. Whether the turn was from the World Cup or Kvitfjell dataset was used as a random variable.

The training set was used to train a linear regression model using the scikit machine learning package in python. One model was created for each dependent variable. The four models were created using the same training set for each model. Each model was tested using k-folds cross validation from the scikit python package with explained variability as scoring parameter.

3. Results

The value of each predictor for each model is shown in table 1. For predicting speed all independent variables but sex was significant to the 0.01 level. Entrance speed had the highest effect on the speed in any turn. After entrance speed gate OFFSET and gate

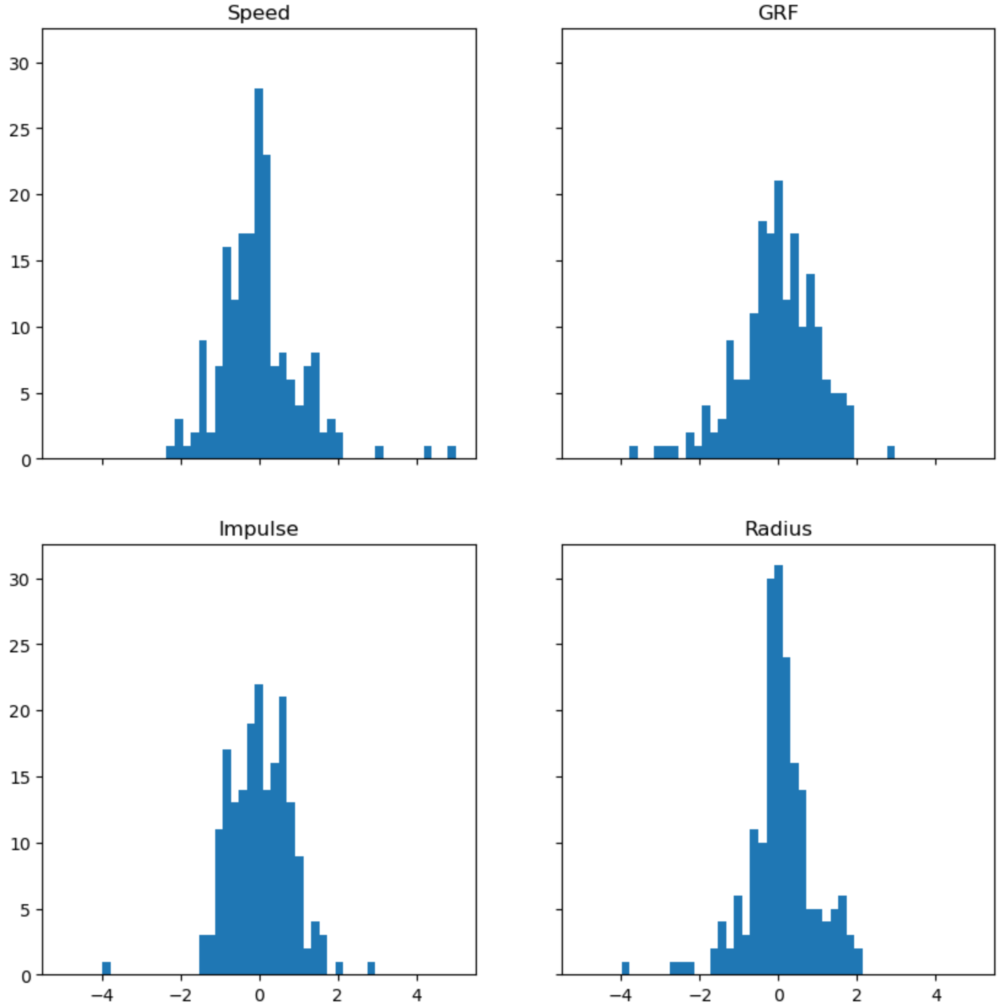

Figure 1: Histogram plot of the residuals of each model. Y-axis: number of predictions, X-axis: Z-score. The X and Y-axis are common for all the plots.

Table 1:Output of each model. The value is expressed as the change in dependent variable as a result of changing the independent variable by one.

Outcome variable	**Predictor**	**Value**
Speed	Intercept	2.70*
	Offset	-0.18*
	Gate distance	0.06*
	Steepness	-0.07*
	Entrance Speed	0.80*
	Sex	-0.08
GRF	Intercept	1.88*
	Offset	0.08*
	Gate distance	-0.02**
	Steepness	-0.01*
	Entrance Speed	0.06*
	Sex	-0.12
Impulse	Intercept	0.97*
	Offset	0.15*
	Gate distance	0.01**
	Steepness	0.00
	Entrance Speed	-0.01
	Sex	0.03
$Radius_{MIN}$	Intercept	-4.46
	Offset	-1.36*
	Gate distance	0.21**
	Steepness	0.09*
	Entrance Speed	1.20*
	Sex	0.62

distance had the 2nd and 3rd highest effect. For predicting GRF_{max}, all independent variables but gate distance was significant with a $p < .01$ and gate distance with $p < .05$. $gate_{OFFSET}$ had the highest effect with entrance speed as the 2nd highest contributor.

For predicting impulse only $gate_{OFFSET}$ was significant with $p < .01$ and gate distance being $p < .05$ level. $gate_{OFFSET}$ had the largest effect on impulse, with gate distance having the 2nd largest effect. For predicting $radius_{MIN}$ $gate_{OFFSET}$, steepness and entrance speed was significant with a $p < .01$ and gate distance with a $p < .05$.

The residuals of the models expressed as the values divided by the standard deviation of the residuals are shown in figure 1. This method of expressing the values was chosen to make the figures easier to compare as the different parameters have different orders of magnitude in raw values and to keep any skewness of the figure. The residual plots show that there are no large outliers in the model and the error has a normal distribution round zero. The model was able to predict the speed of skiers with an r-squared of 0.76, GRF with an r-squared of 0.23, impulse with an r-squared of 0.44 and $radius_{MIN}$ with an r-squared of 0.49. Using k-folds mean cross validation the score of the predictors were 0.62 ± a standard deviation of 0.14 for speed, 0.07 ± 0.13 for GRF_{max}, 0.54 ± 0.07 for impulse and 0.33 ± 0.22 for $radius_{MIN}$. None of the models consistently over or underestimated the parameters. GRF impulse and $radius_{MIN}$ had some large outliers, while speeds had no obvious outliers.

4. Discussion

The model was able to predict speed with high accuracy, impulse and radius with medium accuracy and GRF_{max} with low accuracy. The model was able to predict 62% of the variation in speed, 54% of the variation in impulse, 33% of the variation in $radius_{MIN}$ and 7% of the variation in GRF_{max}.

Among the independent variables entrance speed and gate offset had generally the highest effect on the dependent variables. The only variable for which this was not true was GRF_{max} where the sex of the skier had the biggest impact. Only $gate_{OFFSET}$ had a statistical significant impact on all the dependent variables. However, the correlation between $gate_{OFFSET}$ and GRF_{max} and impulse is positive This means increasing $gate_{OFFSET}$ increases GRF_{max} and impulse. The correlation between $gate_{OFFSET}$ and $radius_{MIN}$ is negative, meaning $radius_{MIN}$ reduces as $gate_{OFFSET}$ increases. Increased GRF_{max}, increased impulse and reduced $radius_{MIN}$ are all associated with increased injury risk of athletes.

As the relationship between gate distance and speed is negative, reducing the gate distance could also be used for reducing the speed of skiers. This method is already stablished as a method for reducing the speed of skiers. However, reducing gate distance had a correlation with higher GRF_{max} it had a very low impact on impulse and $radius_{MIN}$ with a p-value < 0.05.

$Gate_{OFFSET}$ has a higher effect on speed and might seem like a better method for reducing the speed of skiers than gate distance. However, gate distance can be changed by a greater absolute amount than $gate_{OFFSET}$ (Gilgien et al., 2015). Hence, this model on its own does not prove either method to be better than the other. The model does however indicate that both these methods introduce negative effects of increase impulse, GRF_{max} and $radius_{MIN}$. As such the importance of having course-setters with high understanding of the interaction of reducing speed with increasing GRF_{max}, impulse and $radius_{MIN}$ is imperative.

Data from this model was collected on forerunners in world cup competitions or current world cup skiers in a training course. Meaning there are no turns in this data sets collected from world cup skiers in world cup courses, which is the population for which the model attempts to have produce a practical result. The results from this model can therefore not be used directly for prediction in the world cup races. It is not hard to collect data that will solve this problem, because we have course setting data from the 22/23 world cup season and the speed of skiers can be collected with a GNSS or estimated within an acceptable accuracy by extracting the gate times using the TV-broadcast, combined with the gate distance from the course set data.

As shown in figure 1, there were some outliers in the results from all models with outliers defined as more than 3 standard deviations from the mean. With 3 standard deviations as the cutoff for outliers this dataset still has very few outliers with there being 3 outliers in speed, 2 in GRF_{max}, 1 in impulse and 1 in $radius_{MIN}$. This low number of outliers should not have any sizable impact on the results of this model.

While the model's accuracy of speed was high, this prediction is based on the speed in the previous turn. A result of this is the error of the model compounds exponentially over several turns in series. Because of this effect while the model can predict 76% of the variation of speed in a single turn, this falls to 43% over just 3 turns. If the speed in the previous turn is removed from the predictors the accuracy of the model falls dramatically and is no longer usable. As the speed is such an integral part of the model it cannot be implemented before any skier has completed the course. The model was unable to predict impulse and $radius_{MIN}$ with high accuracy.

The model was based on old world cup data, and data from an intervention study with high homogeneity in the turns. These turns might not be representative to how course-setters are setting courses in modern World Cup races.

The lack of tags for delayed gates is a weakness of the model. Delayed gates have different characteristics compared to "normal" gates. The inclusion of such gates in the dataset without the ability to include them as a random effect in the model reduces the performance of the model. These kinds of turns could explain some of the outliers in the dataset. The dataset contains no turns where the data was collected on world cup skiers in a world cup race. Hence the predictability of the model such a situation would be limited.

5. Conclusion

As the model is able to predict speed and impulse with a reasonably high accuracy it might be usable for stakeholders such as coaches and course-setters for predicting the speed and impulse a course experts on athletes. However, its performance for predicting the other dependent variables, is to low to be usable in real world cases. As the model has its weaknesses stakeholders must be vigilant when applying the model. Understanding its possibilities and limitations are imperative for producing results for predicting the parameters in actual World Cup races.

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