Effect of ski geometry on aggressive ski behaviour and visual aesthetics: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing

Josef Kröll, Jörg Spörri, Matthias Gilgien, Hermann Schwameder, Erich Müller

ABSTRACT

Background/Aim Aggressive ski-snow interaction is characterised by direct force transmission and difficulty of getting the ski off its edge once the ski is carving. This behaviour has been suggested to be a main contributor to severe knee injuries in giant slalom (GS). The aim of the current study was to provide a foundation for new equipment specifications in GS by considering two perspectives: Reducing the ski’s aggressiveness for injury prevention and maintaining the external attractiveness of a ski racer’s technique for spectators.

Methods Three GS ski prototypes were defined based on theoretical considerations and were compared to a reference ski (Pref). Compared to Pref, all prototypes were constructed with reduced profile width and increased ski length. The construction radius (sidewall radius) of Pref was ≥27 m and was increased for the prototypes: 30 m (P35), 35 m (P35), and 40 m (P40). Seven World Cup level athletes performed GS runs on each of the three prototypes and Pref. Kinetic variables related to the ski-snow interaction were assessed to quantify the ski’s aggressiveness. Additionally, 13 athletes evaluated their subjective perception of aggressiveness. 15 sports students rated several videotaped runs to assess external attractiveness.

Results Kinetic variables quantifying the ski’s aggressiveness showed decreased values for P35 and P40 compared to Pref and P35. Greater sidewall radius reduced subjectively perceived aggressiveness. External attractiveness was reduced for P40 only.

Conclusions This investigation revealed the following evaluation of the prototypes concerning injury prevention and external attractiveness: Pref: no preventative gain, no loss in attractiveness; P35: substantial preventative gain, no significant loss in attractiveness; P30: highest preventative gain, significant loss in attractiveness.

INTRODUCTION

Skier safety is an important matter for the International Ski Federation (FIS). Since 2006, evidence-based research on injury prevention in competitive skiing has been conducted under the guidance and support of FIS within the “FIS Injury Surveillance System”. According to the sequence of prevention model by van Mechelen et al. research projects have been conducted in the areas of epidemiology and injury causes. On the topic of introducing prevention measures, only one study is currently available. These prevention measures should be based on the aetiological factors and the mechanisms as identified within the injury causes.

Within the classification of severe injuries, the most frequently injured body part was the knee (62.3%), with a particular focus on the rupture of the anterior cruciate ligament (ACL). The majority of knee injuries occur while the skier is still skiing the course (83%). The main mechanism for ACL injury in World Cup alpine skiing was found to be the slip-catch mechanism where the inside edge of the outer ski abruptly catches the snow surface, forcing the outer knee into internal rotation and valgus. In the same study, a similar loading pattern was observed for the dynamic snow plow. Injury prevention efforts should, therefore, focus on the slip-catch mechanism and the dynamic snow plow.

According to the perception of expert stakeholders of the World Cup ski racing community, aggressive ski behaviour is one of the main contributors to the aforementioned injury mechanism. Aggressive ski behaviour is characterised by a too direct force transmission between ski and snow and the phenomenon that the ski becomes difficult to get off its edge once it is carving. As a result, the athlete unable to control the move in the event of an out-of-balance situation due to its self-steering effect, the ski’s behaviour becomes unpredictable. Consequently, it seems reasonable to assume that aggressive ski behaviour favours the ‘catch of the edge’ in an out-of-balance situation.

Less aggressive skis (eg, ones with a greater turning radius), however, are theoretically associated with a decreased self-steering effect, which might affect their performance during controlled skiing (ie, not out-of-balance situations). One could presume that less aggressive skis require a different technique to make them turn and this could potentially result in decreased attractiveness for competitors and spectators.

Therefore, the aim of this study was to provide the decision makers of FIS with an evidence-based foundation for equipment specification changes in giant slalom (GS) by verifying the achievability of the following goal: GS specific injury prevention by a reduction of the ski’s aggressiveness, and maintaining the external attractiveness of ski technique to spectators.

METHODS

Definition of prototypes

In a first step, prototypes were determined, constructed and subsequently analysed. An expert group consisting of researchers, FIS Race Directors
and representatives of the Ski Racing Suppliers Association (SRS) defined the prototypes by considering practical and existing scientific knowledge. The geometrical factors ‘sidecut radius’, ‘ski width’ and ‘ski length’ as well as the mechanical properties ‘homogenous bending line’ and ‘torsional stiffness’ were assumed to be the driving factors for aggressive ski behaviour.\textsuperscript{6 15} The ski’s self-steering effect was assumed to be mainly dependent on the sidecut radius and the ski’s bending characteristics.\textsuperscript{13 14} However, not every technical solution that could potentially reduce the ski’s aggressiveness was viable. Constructive and commercial considerations of SRS, as well as limitations with respect to an appropriate execution of the rules after the competition by FIS lead to certain constraints. Considering these constraints, only three basic geometric variables (length, width and sidecut radius)\textsuperscript{16–18} were altered and experimentally tested as depicted in Table 1. All prototypes were constructed under the guidance of SRS, strictly adhered to by predefined geometrical variables and material composition. Four companies (Atomic, Fischer, Head, Rossignol) produced a full set of prototypes. The corresponding reference ski (Pref) represented the equipment used at the time of this study. The deeper the reverse camber (by sidecut radius and/or edge angle), the faster the ski will turn due to the more pronounced self-steering effect\textsuperscript{14 15} and results in a more evident loading at where forces are transmitted in and between equipment and skier. Therefore, measuring ground reaction forces for quantifying aggressive ski behaviour would seem to be reasonable.

For the current study pressure insoles were used to quantify local loads between the foot and the ski boot (PEDAR; Novel; 100 Hz). Based on the pressure values the following forces were calculated relative to body weight (BW) (figure 2): Total ground reaction force ($F_{tot}$), ground reaction force of the outside leg ($F_{out}$), and the $F_{out}$ portion at the forefoot ($F_{outaft}$) and rearfoot ($F_{outaf}$). The pressure insoles used are known to underestimate the real force values.\textsuperscript{22} Nevertheless, for a dependent (ie, different skier’s) study design with high level athletes, the applied method can be considered adequate, since it minimally impairs the athletes during movement execution and, additionally, the areas of force transmission can be depicted. Turn separation was performed based on the functional minima of $F_{out}$ during edge change.\textsuperscript{23} Time-normalised data were subsequently divided into four phases based on previously reported kinematic data in GS: 0–23% Initiation; 23–52% COM Direction Change I; 52–82% COM Direction Change II; 82–100% Completion.\textsuperscript{12 24} Parameter calculation and post-processing were performed using MATLAB R2012b (MathWorks).

For each athlete and condition, average curves were calculated. Based on these individual average curves, group mean values along the overall turn pathway were calculated and graphically visualised as average curve±SE. The mean values of the specific turn phases were reported as mean±SD and were tested for significant differences (p<0.05). For each turn phase, repeated measures multivariate ANOVA (MANOVA) (dependent $F_{tot}$/$F_{outaft}$/$F_{outaf}$ independent $F_{ref}/P_{30}/P_{35}/P_{40}$) were calculated. In case of global significance, a one-way repeated measures ANOVA ($F_{ref}/P_{30}/P_{35}/P_{40}$) was performed on each variable, including post hoc testing with Bonferroni correction. Furthermore, ANOVA with post hoc testing was applied on the distance (difference) of two adjacent ski geometries ($F_{ref}/P_{30}/P_{35}/P_{35}/P_{40}$)

To determine the degree of representativeness of the experimental setup to World Cup conditions, speed was measured for one skier (skiing with $P_{ref}$) using dynamic dGNSS and course setting was characterised using static dGNSS.\textsuperscript{25} Median (±IRQ)

### Table 1 Specification of the basic geometric parameters of the giant slalom skis used for the experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$P_{ref}$*</th>
<th>$P_{30}$</th>
<th>$P_{35}$</th>
<th>$P_{40}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ski length (mm)</td>
<td>1910±7</td>
<td>1950</td>
<td>1950</td>
<td>1950</td>
</tr>
<tr>
<td>Ski width (mm)</td>
<td>67.1±0.2</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Sidecut radius (m)</td>
<td>28.7±0.3</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
</tbody>
</table>

* $P_{ref}$ represents the original racing skis of the companies that have been mandated by SRS to serve the equipment for the experiments. Therefore, there were small variations in the geometrical variables ski length, ski width and sidecut radius between the companies (Mean±SD). $P_{ref}$ were in accordance with the legal specification valid until Season 2011/12: Sidecut radius ≥27 m; Ski length ≥185 cm; Ski width ≥65 mm.
gate distance (25.44±0.81 m) and median horizontal gate distance (7.13±1.16 m) were slightly shorter than in average GS World Cup course settings (26.24±2.25 m and 7.47±2.93 m, respectively).\textsuperscript{26} Median terrain inclination (−23.3°±1.9°) was a bit steeper compared to GS World Cup races (−17.8°±7.0°).\textsuperscript{26} Median skier speed (18.0°±1.2 m/s) was close to GS World Cup racing (17.75±2.3 m/s).\textsuperscript{72}

**Determination of external attractiveness (experiment 3)**

Twenty sports students regularly following GS events on TV participated in this study. A set of 28 videos conducted during the biomechanical experiment; 5 gate section; n=7×(Pref+P30+P35+P40) were presented to the participants several times: Session1 and Session2 were used to prime the participants with respect to the spectrum of the 28 videos. During Session3 and Session4, participants rated the randomised video via VAS (figure 3). Each video was presented three times (original speed; reduced speed; original speed) with a subsequent rating period of 15 s. Within Session 3 and Session 4, a break of 5 min was permitted, and between the sessions a break of 15 min was given.

To evaluate the rater reliability of participants, individual correlations on the 28 VAS values between Session3 and Session4 were calculated, which resulted in the exclusion of five participants with r<0.7. The VAS values from the remaining 15 participants were finally tested for statistical differences (Session3). The significance of the VAS value on external attractiveness was tested with a two-way repeated measures ANOVA (4 (Pref/P30/P35/P40)×7 (athletes); p<0.05) including post hoc analysis with Bonferroni correction.

**RESULTS**

**Determination of subjectively perceived aggressive ski behaviour (experiment1)**

The ANOVA and all pairwise comparisons revealed significant differences in the overall aggressiveness scores (figure 4). The VAS scores decreased with greater sidecut radius (Pref>P30>P35>P40). The perceived aggressiveness decreased almost linearly with sidecut radius increase, so the score distances between two adjacent ski geometries did not reveal significant differences (p>0.175; \(\eta^2=0.272\)).

**Biomechanical quantification of aggressive ski behaviour (experiment 2)**

The time-courses of ground reaction force for the four ski sample are presented in figure 5. Generally, all ground reaction force parameters decreased with greater sidecut radius, especially in the phases after gate passage. This observation is supported by the MANOVA results for the specific turn phases: no
significance for Initiation (p<0.225, η²=0.201) and COM Direction Change I (p<0.078, η²=0.245); but significance for COM Direction Change II (p<0.022, η²=0.331); and Completion (p<0.014, η²=0.349).

During COM Direction Change II the subsequent ANOVAs revealed significant differences for F_out, F_outfore and F_outaft, but not for F_tot (table 2). Post hoc comparison did not reveal significant differences between P_ref and P_30 and between P_35 and P_40 for any parameter. From all other pairwise comparisons, greatest differences were observed for F_outaft (from −11.2% up to −17.2%; table 2). For this parameter, the distances of two adjacent ski geometries also were significant (p<0.028, η=0.831): P_ref→P_30 (0.02BW±0.04) is significantly smaller (p<0.042) compared to P_30→P_45 (0.11BW±0.04); P_30→P_35 is significantly greater (p<0.048) compared to P_35→P_40 (0.03BW±0.02); no significant difference between P_ref→P_30 and P_35→P_40.

**Determination of external attractiveness (experiment 3)**

The two-way ANOVA and some of the post hoc analyses revealed significant differences for external attractiveness (figure 6). For the factor ski, no differences were found for F_ref, F_30 and P_35. P_30, however, was significantly less attractive compared to all other skis.

**DISCUSSION**

The main findings of this study were: (1) a combination of small alterations in ski length, ski width and sidecut radius (P_ref vs P_30) was found to lead to an altered perception of the ski’s aggressiveness, but not to a significant decrease in the biomechanically quantified aggressiveness; (2) a substantially greater sidecut radius (35m and 40m) led to a decrease in the perception of the ski’s aggressiveness accompanied by a reduction of ground reaction force after gate passage, particularly under the forefoot of the outside leg; (3) the forces acting under the forefoot did not decrease linearly with greater sidecut radius (P_30→P_35→P_40); (4) external attractiveness was significantly decreased only when skiing with P_40.

**Quantifying an aggressive ski behaviour**

The sidecut radius is one of the most important variables of ski geometry because it largely determines how a ski turns. To some extent, this was verified by this study as well, since the intervention according to ski width and ski length (P_30) did not reveal significant differences with respect to the biomechanical measures compared to P_ref.

As a ski is tipped up on its edge and pressed against the snow surface, the sidecut radius allows the ski into a reverse camber position and makes the ski turn as it moves forward. This is called the ski’s self-steering effect. In the context of injury mechanisms, this behaviour is also of interest. By catching the inside edge in an out-of-balance situation, a carving ski rotates inward and can produce an internal tibial torque, which was identified as ‘aggressive ski behaviour’. In other words, the functionally positive associated term ‘self-steering effect’ while controlled skiing becomes negatively associated in the case of out-of-balance situations and is then called ‘aggressive ski behaviour’. Strictly speaking, this study explored the self-steering effect of different ski geometries in controlled skiing situations. The ski’s aggressiveness, therefore, was only indirectly explored. It has to be mentioned, that an assessment of aggressiveness in out-of-balance situations is experimentally difficult to perform and ethically not justifiable since it would consciously force the athlete into a risk position of severe injury.

As described from a mechanical perspective in the methods, F_outfore seems to be a reasonable measure of the self-steering effect and, therefore, an estimate of aggressive ski behaviour. The decrease in F_outfore with greater sidecut radius supports the argument above: while skiing with greater sidecut radius, the self-steering effect is less pronounced and consequently the body of the ski does penetrate and shear the snow less. Thus, the resulting effect of inertia in the direction of travel is reduced, the outcome of which is lower forces under the forefoot. The advantage of this approach compared to the rating of perceived aggressiveness is obvious: results are subjectively unbiased and the parameter seems to be more sensitive to the evaluation of subtle differences, since differences between
the distances of the skis used also were identified ($P_{30} \bowtie P_{35} \bowtie P_{40}$), which was not the case for perception.

Theoretical approaches usually neglect the possibility of intuitively distributing the load on both the inside and outside leg. Although the inside leg loading obtained attention in connection with steering a ski with small sidecut radius, the outside leg is still mainly responsible for steering. The inside leg is used primarily to support the outside leg; for instance, to avoid falling too far to the inside if the direction of the resultant forces do not match whole body inclination. Hence, it is plausible to observe the main differences of the self-steering effect on the outside leg. In the current study the greatest differences were observed with respect to this phenomenon (significant for $F_{\text{out}}$ and $F_{\text{out,fore}}$).

Interestingly, the theoretical considerations for skiing pure carved turns match best with the phase of COM Direction Change II. Several theoretical approaches—always presuming pure carving without skidding—demonstrated that greater sidecut radius leads to decreased ground reaction force. Once a skier passes the fall line (the beginning of COM Direction Change II), the edge angles typically increase, and lean angles reach the highest values. During this phase, skid angle, as well as turn radius, usually show the lowest values resulting in high amounts of carving. This explains the most pronounced differences observed in this study for that phase and seems to be an adequate model for investigating the self-steering effect, and consequently, for investigating the aggressiveness of various skis. From an injury prevention point of view, this phase is also of particular interest because more than half of the ACL-injuries occur while turning, mainly during the steering phase out of the fall line.

**Ski geometry as an injury prevention measure**

An earlier study comparing the most extreme horizontal gate distances in GS concluded that as long as the course setting changes were not substantial enough, injury risk might not be reduced considerably, since athletes are still able to adapt and partly compensate by changing their timing strategy. In contrast, more substantial changes might leave the borders of usual technical solutions and athletes would have to adapt their skiing technique substantially. The adapted technical solutions could potentially be less attractive for the spectators. Therefore, to minimise injury risk while maintaining attractiveness are challenges for decision-makers and must be considered carefully.

To our knowledge, the strategy of assessing both aspects prior to introducing the prevention measure is unique and was performed for the first time in alpine ski racing by the current study. Our results revealed that potential gains in injury prevention and the beginning of a loss of attractiveness occur on different levels of intervention: from a prevention perspective, a sidecut radius of 35 m provides substantial gain (highest distance between $P_{30}$ and $P_{35}$); from an attractiveness perspective, a significant loss was observed only for a 40 m sidecut radius accompanied with moderate additional reduction of injury risk compared to $P_{35}$. This difference is important for the decision-makers of FIS in terms of balancing performance and injury related arguments against each other.

For decades, as the governing body of international ski competition, FIS has set limits on different geometrical parameters of racing skis by citing injury prevention concerns. Despite the sustained efforts (eg, revised specifications 2003 and 2007), injury rates were reported to be alarmingly high for six consecutive seasons (2006–2012). Earlier revisions of the equipment...
CONCLUSION

This study explored the aggressiveness of different ski geometries while skiing a typical GS course. An ‘aggressive’ ski behaviour in out-of-balance situations is associated with a direct force transmission at the ski-snow interaction and is known to be a main risk factor for severe knee injuries in GS. The ground reaction forces under the forefoot of the outside leg seem to be an innovative and reasonable measure to quantify the aggressiveness of skis. Compared to assessing the athletes’ perceptions, the aforementioned measure is more subtle and free of subjective bias.

Furthermore, data from this study showed that potential gains in injury prevention by reducing the ski’s self-dynamic effect (aggressive ski behaviour in an out-of-balance situation) and the beginning of the loss of attractiveness for the spectator occur on a different level of intervention. Consequently, for the decision-makers of FIS this investigation suggested three evidence-based arguments: (1) P30: no preventative gain, no loss in attractiveness; (2) P35: substantial preventative gain, no significant loss in attractiveness; (3) P40: highest preventative gain, significant loss in attractiveness.

Acknowledgements The authors would like to thank Rüdiger Jahnel, Peter Scheiber, Christoph Eiter and Atle Skaardal for their on-hill support and SRS for organising the prototype production and athlete recruitment.

Contributors JK, JS and EM conceptualised the study design. JK organised and coordinated the biomechanical field study. JK, JS, MG contributed to the data collection. JK, supported by JS and MG conducted the data processing and analysis. All authors contributed the intellectual content of the study, manuscript writing and approved the final version of this article.

Funding This study was financially supported by the International Ski Federation (FIS).

Competing interests None declared.

Ethics 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.

Open Access This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/
REFERENCES


Effect of ski geometry on aggressive ski behaviour and visual aesthetics: equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing

Josef Kröll, Jörg Spörrri, Matthias Gilgien, Hermann Schwameder and Erich Müller

doi: 10.1136/bjsports-2015-095433

Updated information and services can be found at:
http://bjsm.bmj.com/content/50/1/20

These include:

**Open Access**

This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/

**Email alerting service**

Receive free email alerts when new articles cite this article. Sign up in the box at the top right corner of the online article.

**Topic Collections**

Articles on similar topics can be found in the following collections

- Open access (266)
- Health education (481)
- Injury (957)
- Knee injuries (92)
- Trauma (845)

**Notes**

To request permissions go to:
http://group.bmj.com/group/rights-licensing/permissions

To order reprints go to:
http://journals.bmj.com/cgi/reprintform

To subscribe to BMJ go to:
http://group.bmj.com/subscribe/