Effect of ski geometry and standing height on kinetic energy: equipment designed to reduce risk of severe traumatic injuries in alpine downhill ski racing

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ABSTRACT

Background Injuries in downhill (DH) are often related to high speed and, therefore, to high energy and forces which are involved in injury situations. Yet to date, no study has investigated the effect of ski geometry and standing height on kinetic energy (E_{KIN}) in DH. This knowledge would be essential to define appropriate equipment rules that have the potential to protect the athletes' health.

Methods During a field experiment on an official World Cup DH course, 2 recently retired world class skiers skied on 5 different pairs of skis varying in width, length and standing height. Course characteristics, terrain and the skiers' centre of mass position were captured by a differential Global Navigational Satellite System-based methodology. E_{KIN}, speed, ski–snow friction force (F_F), ground reaction force (F_{GRF}) and ski–snow friction coefficient ($Coeff_F$) were calculated and analysed in dependency of the used skis.

Results In the steep terrain, longer skis with reduced width and standing height significantly decreased average E_{KIN} by ~3%. Locally, even larger reductions of E_{KIN} were observed (up to 7%). These local decreases in E_{KIN} were mainly explainable by higher F_F. Moreover, $Coeff_F$ differences seem of greater importance for explaining local F_F differences than the differences in F_{GRF}.

Conclusions Knowing that increased speed and E_{KIN} likely lead to increased forces in fall/crash situations, the observed equipment-induced reduction in E_{KIN} can be considered a reasonable measure to improve athlete safety, even though the achieved preventative gains are rather small and limited to steep terrain.

INTRODUCTION

Alpine ski racing is known to be a sport with a high risk of sustaining severe injuries.[1 2] Injury rates for World Cup (WC) athletes were found to differ among the competition disciplines, particularly when calculated as injuries per 1000 runs: they increased from slalom to giant slalom, super-G and downhill (DH) with the knee as the most frequently injured body part.[1] However, if injury risk is normalised with risk exposure time and calculated as the number of injuries per time skiing, the disciplines giant slalom, super-G and DH can be considered to be equally dangerous but for different reasons.[3]

With respect to the injury causes, a recent study assessing the skier biomechanics in WC alpine skiing found that injuries in super-G and DH are most likely due to high speeds, jumps and higher workloads caused by long competition times.[3] High speed is expected to shorten the preparation time necessary for the skier to adapt to jumps and demanding course sections.[3] High speed is also expected to increase jump length and air time, resulting in an increased risk of falling.[3 4] Furthermore, high speed and, therefore, high kinetic energy ($E_{KIN}=1/2\times mass\times speed^2$) are likely to increase the forces that occur at the impact in fall or crash situations.[3] Consequently, reducing E_{KIN} can be considered a potential prevention tool, particularly in super-G and DH.[3]

Thus far, it is known that course setting might be an effective preventative measure to control skier speed and E_{KIN} in steep terrain in DH courses.[5 6] In addition, equipment-related measures, namely different ski geometries and standing height (ie, distance from ski base to binding plate cover), might potentially reduce E_{KIN}/speed, as was hypothesised by expert stakeholders of the WC ski racing community.[7] Yet to date, scientific knowledge on DH is very limited,[3–6 8–10] and no field study has assessed equipment-related, preventative measures in super-G and DH.

Therefore, this study aimed to investigate the effect of modifications in ski geometry (ski length, ski width) and standing height of DH skis on speed and E_{KIN} while skiing a WC DH course.

METHODS

Measurement protocol and data collection

Two recently retired (10 months) male WC athletes (age: 34.5±4.5 years; height: 184±2 cm; weight: 98.5±1.5 kg) skied several runs on five different pairs of skis varying in width (W), standing height (H) and length (L). For each skier, 4 runs per ski were considered for the data analysis (ie, a total of 40 runs). The test order of the skis was randomised and snow conditions were monitored. The reference ski (SKI_{REF}) was built according to the International Ski Federation (FIS) equipment rules being valid until Winter Season 2011/2012.[11] The specifications of all other skis were defined by an expert group consisting of representatives of the Ski Racing Suppliers Association (SRS), FIS Race Directors and researchers who took into consideration the existing scientific knowledge and practical experience (table 1). All prototypes were constructed by one company under the guidance of SRS, strictly adhered to the predefined geometrical variables (table 1) and material composition.

The biomechanical field experiment was conducted on the lower part of the FIS WC DH course in Åre (Sweden), directly after a women's WC DH race. The first section of the course was

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Table 1 Specification of the basic geometric parameters of the DH skis used for the experiments

	SKI_{REF}*	SKI_{WH}	SKI_{LH}	SKI_{WL}	SKI_{WLH}
Width (mm)	69	65	69	65	65
Standing height (mm)	50	40	40	50	40
Length (cm)	216	216	220	220	220

*Ski_{REF} represents the original DH racing skis according to the FIS equipment rules valid until Winter Season 2011/2012.[8]
DH, downhill; FIS, International Ski Federation; SKI_{REF}, reference ski.

steep and turning ($Section_{STEEP}$), the second section was flat and less turning ($Section_{FLAT}$; figure 1). The analysis for $Section_{STEEP}$ started at the first gate where skiers reached 19.9 m/s and ended at gate number 9. The analysis of $Section_{FLAT}$ started at gate 11 and ended at gate 21.

Course setting and the snow surface geomorphology were captured using static differential global navigation satellite systems (dGNSS) and were reconstructed in a digital terrain model (DTM), as conducted in earlier studies.[5 6] Each skier's instantaneous three-dimensional position was captured by kinematic dGNSS (50 Hz), using GPS and the Russian (GLONASS) global navigation satellite systems, L1 and L2 signals, and was carried in a small backpack as described in detail in previous studies.[12 13] The centre of mass (CoM) position of the skier was approximated using a virtual pendulum model, which was attached to the skier's antenna position and the intersection of the pendulum with the snow surface DTM.[12]

Postprocessing and parameter calculations

Course setting was characterised by gate distance and horizontal gate distance,[14 15] using the definition of double gate turns in speed disciplines introduced in earlier studies.[5 6 16] Skier speed, turn radius and E_{KIN} were derived from the CoM position (measurement-system accuracy: 0.1 m).[12] Ground reaction force

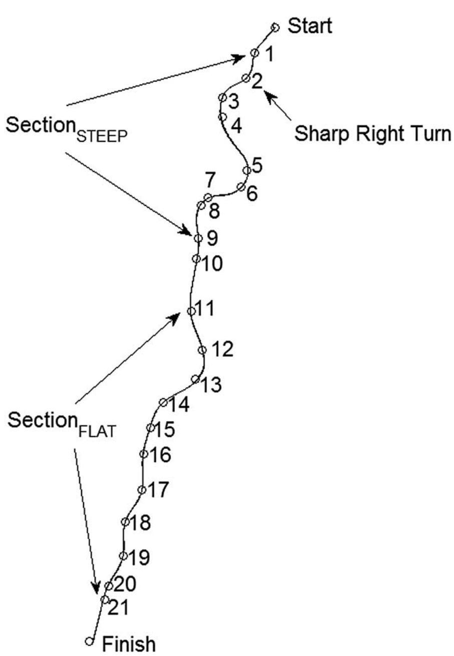

Figure 1 Map of the course with gates, gate numbers and skier trajectories. The boundaries of the steep section ($Section_{STEEP}$) and the flat section ($Section_{FLAT}$) and the sharp right turn at gate 2 are indicated with arrows.

Table 2 Characteristics of the course for the steep ($Section_{STEEP}$) and the flat ($Section_{FLAT}$) sections of the downhill course

Parameter	Entire course	
Course length (m)	1302	
Vertical drop (m)	402	
Number of gates ( )	21	
Mean run time (s)	50.0	
	$Section_{STEEP}$	**$Section_{FLAT}$**
Median terrain inclination (°)	−23	−15
Median gate distance (m)	84.23	61.67
Median horizontal gate distance (m)	35.65	12.23
Mean direction change from gate to gate (°)	23	11

(F_{GRF}) and ski–snow friction force (F_F) were calculated by the application of a kinetic model on the CoM position, the virtual pendulum model and the body extension (measurement-system accuracy: 63N for F_{GRF}; 42N for F_F).[17] The ski–snow friction coefficient ($Coeff_F$) was calculated as the coefficient of F_F and F_{GRF}.[16] To compare the time series data of speed, turn radius, E_{KIN}, F_{GRF}, F_F and $Coeff_F$, between runs, parameters were spatially normalised based on an alternative approach specifically dedicated to the characteristics of competitive alpine DH skiing (see online supplementary data).

Statistical analysis

The statistical analysis was conducted for skiers A and B and for $Section_{STEEP}$ and $Section_{FLAT}$ separately. For each run of each skier and each ski, E_{KIN} averages of the $Section_{STEEP}$ and $Section_{FLAT}$ were calculated. Based on these single E_{KIN} section averages, participant mean±SD values were computed for all tested skis. In addition, E_{KIN} section averages were tested for significant differences between the tested skis using a one-way analysis of variance (ANOVA; $p<0.05$). For pairwise comparison, the post hoc Tukey-Kramer correction was used. To assess if the response to the ski intervention was similar for both skiers, the average E_{KIN} difference between SKI_{REF} and each ski type was compared between the skiers for each section. To test whether these ski response differences between the skiers were statistically significant, two-sided Student t tests ($p<0.05$) were used.

Finally, a local subsection in which the equipment-induced effects on E_{KIN} seemed to be the greatest was defined. Within this subsection (the sharp right turn at gate 2), the relation between E_{KIN} and the E_{KIN} explanatory parameters were investigated by the use of: (1) Spearman's rank correlation coefficients between the $_{WLH}SKI_{WLH}-SKI_{REF}$ differences in speed and the $_{WLH}SKI_{WLH}-SKI_{REF}$ differences in F_F; and (2) a multiple

Table 3 Characteristics of speed and kinetic energy (E_{KIN}) for the course sections steep ($Section_{STEEP}$) and flat ($Section_{FLAT}$)

Parameter	$Section_{STEEP}$		$Section_{FLAT}$	
Group mean of E_{KIN} (J/BW)	30.9		44.7	
Group mean of speed (m/s)	24.6		29.6	
	Skier A	**Skier B**	**Skier A**	**Skier B**
E_{KIN} (J/BW)	31.1	30.6	45.3	41.1
Speed (m/s)	24.7	24.5	29.8	29.4

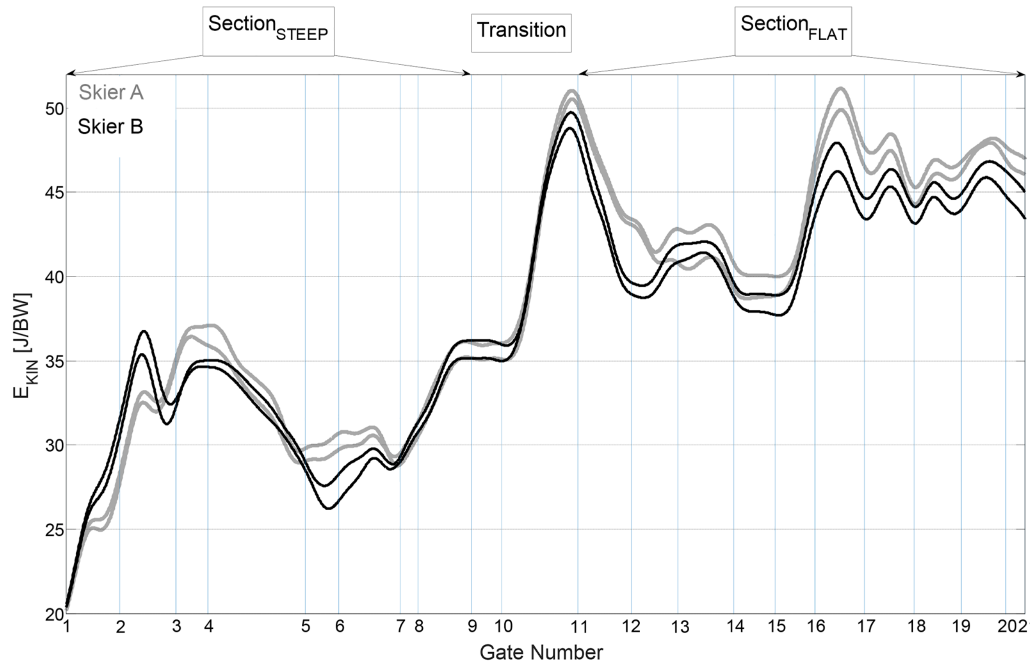

Figure 2 Areas around the estimate of the mean (±SE) illustrating instantaneous kinetic energy (E_{KIN}) for both skiers skiing on reference ski. Grey lines: skier A; black lines: skier B. The boundaries of the steep section (Section$_{STEEP}$), the transition between sections and the flat section (Section$_{FLAT}$) are indicated at the top of the figure.

regression analysis assessing the contribution of differences in $Coeff_F$ and in F_{GRF} to explain the local differences in F_F between SKI_{REF} and SKI_{WLH}.

RESULTS

General characteristics of the test setup

Table 2 presents the course characteristics of the test setup on the WC DH course. Table 3 shows the average speed and E_{KIN} within Section$_{STEEP}$ and Section$_{FLAT}$ for both skiers. Figure 2 illustrates the instantaneous E_{KIN} (ie, its mean±SE from start of Section$_{STEEP}$ to end of Section$_{FLAT}$ for both skiers using SKI_{REF}). It can be visually observed that E_{KIN}/speed was higher in Section$_{FLAT}$ than Section$_{STEEP}$, and that instantaneous differences between the skiers were present at various locations of the course.

Differences in E_{KIN} between the tested skis within specific sections of the course

The results reporting the E_{KIN} section average differences between the tested skis are shown in table 4. The one-way ANOVA analysis was significant for both skiers for Section$_{STEEP}$, but not for Section$_{FLAT}$, indicating that the equipment intervention did not have an effect on E_{KIN}/speed in Section$_{FLAT}$. At the pairwise comparisons (right side of table 4), a difference is negative if the modified skis showed smaller E_{KIN} mean values than SKI_{REF}. The only ski prototypes that caused a statistically significant reduction in E_{KIN}/speed compared with SKI_{REF} was SKI_{WLH}. This finding was independently observed for both skiers in Section$_{STEEP}$ only (skier A: −0.95 J/BW, −3.0%; skier B: −1.0 J/BW, −3.2%).

The extent to which a certain pair of skis caused the same E_{KIN}/speed difference with respect to SKI_{REF} was not significantly different between skiers but was significantly smaller in Section$_{STEEP}$ (0.07±0.03 m/s) than in Section$_{FLAT}$ (0.21±0.08 m/s).

Differences in E_{KIN} between SKI_{WLH} and SKI_{REF} in Section$_{STEEP}$

Figure 3 illustrates the instantaneous differences in E_{KIN} between SKI_{REF} and SKI_{WLH} for skiers A and B within

Table 4 Top: statistical analysis comparing the E_{KIN} for skiers A and B in the Section$_{STEEP}$. Bottom: statistical analysis comparing the E_{KIN} for skiers A and B in the Section$_{FLAT}$

	E_{KIN} (J/BW)					ANOVA	Pairwise comparisons (%)			
Ski	SKI_{REF}	SKI_{WH}	SKI_{LH}	SKI_{WL}	SKI_{WLH}	p Value	$SKI_{WH}-SKI_{REF}$	$SKI_{LH}-SKI_{REF}$	$SKI_{WL}-SKI_{REF}$	$SKI_{WLH}-SKI_{REF}$
Section$_{STEEP}$										
Skier A	31.35±0.30	31.15±0.04	31.44±0.24	31.65±0.37	30.40±0.43	.001***				−3.0*
Skier B	31.08±0.18	31.15±0.04	31.05±0.25	31.2±0.42	30.08±0.55	.005***				−3.2*
Section$_{FLAT}$										
Skier A	45.24±0.47	45.47±0.61	45.67±1.01	46.32±0.08	45.10±0.64	0.209				
Skier B	43.30±0.96	45.07±0.61	44.54±0.15	44.96±1.30	44.70±0.73	0.108				

Level of significance: *p<0.05, **p<0.01, ***p<0.001. Post hoc method with Tukey-Kramer correction for pairwise comparison.
The mean±SD of E_{KIN} is given for each prototype and course section on the left side. The right side presents selected pairwise ANOVA comparisons of SKI_{WH}, SKI_{LH}, SKI_{WL} and SKI_{WLH} with SKI_{REF}. A difference is negative if the modified skis showed smaller E_{KIN} mean values than when skiing on SKI_{REF}.
ANOVA, analysis of variance; E_{KIN}, kinetic energy; Section$_{FLAT}$, flat course section; Section$_{STEEP}$, steep course section; SKI_{REF}, reference ski.

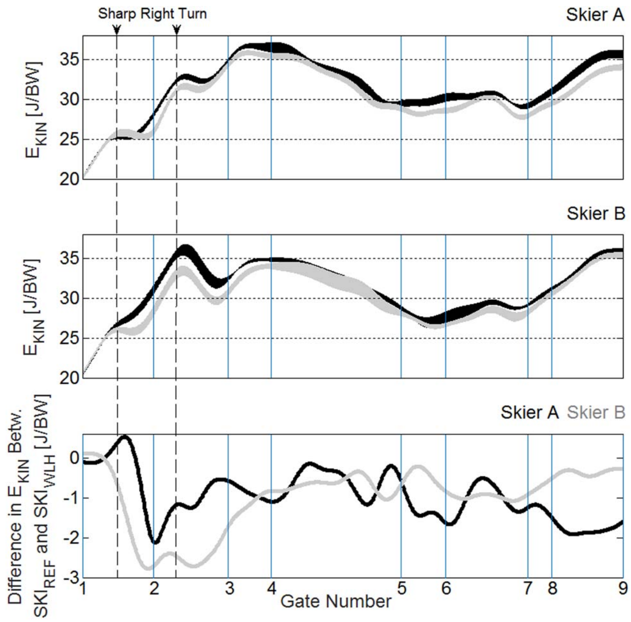

Figure 3 Top (skier A) and middle (skier B): areas of uncertainty around the estimate of the mean (±SE) illustrating instantaneous kinetic energy (E_{KIN}) and reference ski (SKI_{REF}) versus SKI_{WLH} within steep section. Black area: SKI_{REF}; grey area: SKI_{WLH}. Bottom: instantaneous differences between SKI_{REF} and SKI_{WLH} for skier A (black line) and for skier B (grey line). The dashed lines indicate the sharp right turn at gate 2.

$Section_{STEEP}$. The specific subsection 'sharp right turn' starts at the first gate, where mean speed is equal for both skiers and skis (skier A: 19.9 m/s with SKI_{REF} and 19.9 m/s with SKI_{WLH}; skier B: 20.0 m/s with SKI_{REF} and 20.0 m/s with SKI_{WLH}), and ends when the average turn radius of both skiers and skis exceeded 125 m after the passage of gate 2. Within this subsection, the percentage differences in E_{KIN} between SKI_{WLH} and SKI_{REF} were −3.6% for skier A and −7.0% for skier B.

Table 5 shows the Spearman's rank correlation coefficients describing the relation between the SKI_{WLH}−SKI_{REF} differences in speed and the corresponding differences in F_F during the sharp right turn in the steep section for skiers A and B. For skier B, speed was significantly correlated with F_F.

Table 6 shows the results of the multiple regression analysis assessing the contribution of the $_{WLH}SKI_{WLH}$−SKI_{REF} differences in $Coeff_F$ and in F_{GRF} to explain the $_{WLH}SKI_{WLH}$−SKI_{REF} difference in F_F during the exemplary sharp right turn. This analysis indicated that the differences in $Coeff_F$ were more important than those in F_{GRF} to explain the differences in F_F (figure 4).

Table 5 Spearman's rank correlation coefficients describing the relation between the SKI_{WLH}−SKI_{REF} differences in speed, and the differences in F_F during the sharp right turn at gate 2 for skiers A and B

Skier A	*Speed*
F_F	0.800$^{n.s.}$
Skier B	*Speed*
F_F	1.000**

Level of significance: ^{ns}not significant at p<0.05, *p<0.05, **p<0.01, ***p<0.001.
F_F, ski–snow friction force; SKI_{REF}, reference ski.

DISCUSSION

The main findings of the study were that no difference between the tested skis on average E_{KIN} in $Section_{FLAT}$ were observed, but SKI_{WLH} caused a ~3% E_{KIN} reduction for both skiers in $Section_{STEEP}$ compared with SKI_{REF}. No other differences between SKI_{REF} and the ski prototypes were observed. The largest reduction in E_{KIN} was found in a sharp right turn at gate 2 for skier B (−7.0% for skier B; −3.6% for skier A). For skier B, this reduction in E_{KIN}/speed can be explained by increased F_F, which was mainly a result of increased $Coeff_F$.

The progress of E_{KIN} over the entire DH course

The current study revealed that for both skiers E_{KIN}/speed was lower in $Section_{STEEP}$ than in $Section_{FLAT}$ (table 3), which is in line with previous findings in men's WC alpine skiing.[5 6 18] Moreover, based on the study findings presented in tables 2 and 3, speed, terrain and course setting can be considered representative for both female and male WC races.[5 6]

Comparing the individual progressions of E_{KIN}/speed between skiers A and B when skiing on SKI_{REF}, it seems that the general characteristics correspond well, but locally differ at certain spots along the course. A similar observation was already reported for other energy-related parameters in giant slalom by Supej.[19] Additional analysis revealed that these interindividual differences in E_{KIN}/speed on SKI_{REF} were generally larger than the differences caused by the ski intervention. The agreement in response to the ski intervention between skiers was best in $Section_{STEEP}$ where the significant speed reductions were found between SKI_{WLH} and SKI_{REF} for both skiers. These two aspects might strengthen faith in the findings of this study.

The effect of ski geometry and standing height on E_{KIN}

Effects over the entire DH course

As shown in this study, none of the tested pairs of skis caused significant differences compared with SKI_{REF} in $Section_{FLAT}$. However, a significant reduction of ~3% in E_{KIN} was found for the prototype with all three parameters altered (SKI_{WLH}) in $Section_{STEEP}$ (table 4). Furthermore, postanalysis for $Section_{STEEP}$ revealed that the tested ski interventions had the smallest effect on E_{KIN}/speed in the traverse (ie, between gates 4 and 5). Hence, the combination of steep terrain and turning courses seems to provoke differences between the modified skis and SKI_{REF}, while flat terrain in combination with 'gliding turns' (ie, turns, which can be skied in a tucked position) do not.

Table 6 Results of the multiple regression analysis assessing the contribution of differences in the average ski–snow friction coefficient ($Coeff_F$) and in the average ground reaction force (F_{GRF}) to explain the difference in average ski–snow friction force (F_F) between reference ski (SKI_{REF}) and SKI_{WLH} during the sharp right turn at gate 2

Predictors of F_F	β-weight	p Value
Skier A		
$Coeff_F$	1.011	0.004
F_{GRF}	0.123	0.011
Skier B		
$Coeff_F$	0.944	0.006
F_{GRF}	−0.320	0.019

Model for skier A: adjusted R^2=1.000; p=0.012.
Model for skier B: adjusted R^2=1.000; p=0.010.

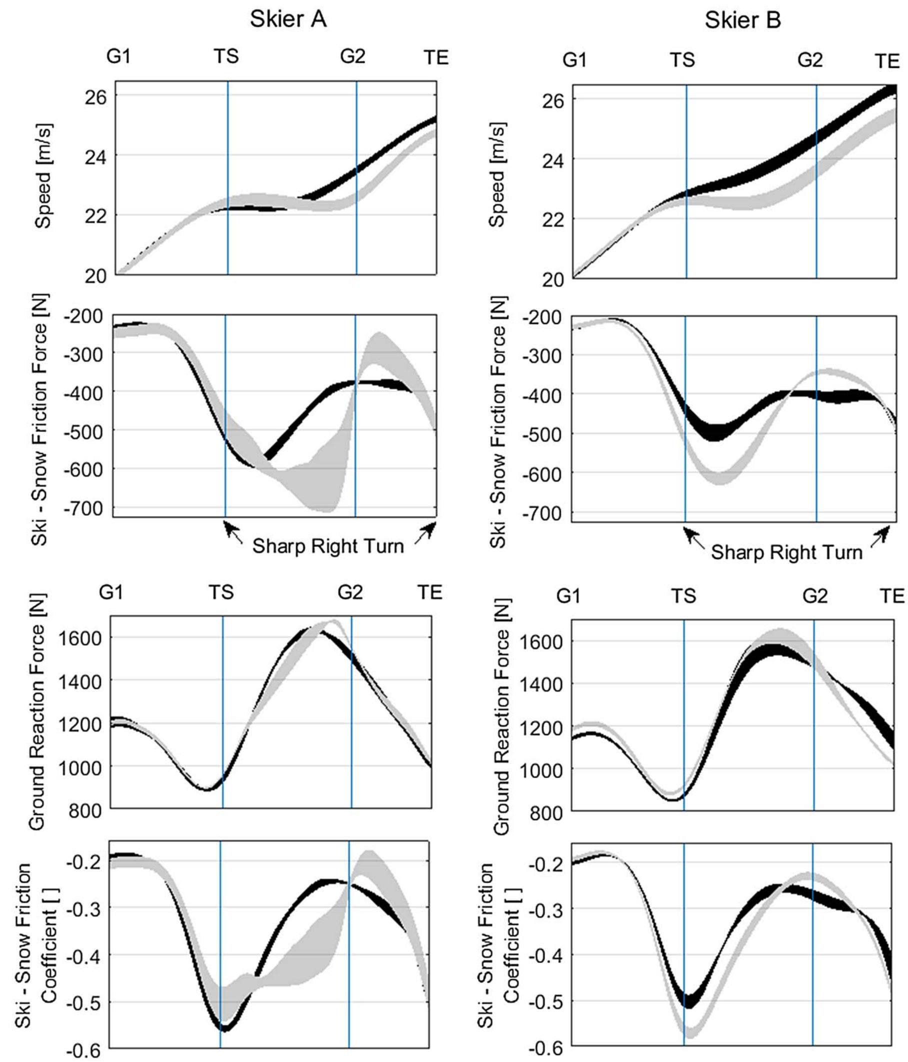

Figure 4 Areas of uncertainty around the estimate of the mean (±SE) illustrating speed, ski–snow friction force (F_F), ground reaction force (F_{GRF}) and ski–snow friction coefficient ($Coeff_F$). Black area: reference ski; grey area: SKI_{WLH}. The in-depth analysis of speed and F_F, as well as F_{GRF} and $Coeff_F$ for skier A (left side) and skier B (right side) are presented for the exemplary sharp right turn in steep section. G1 and G2 indicate gates 1 and 2, TS and TE indicate turn start (when mean turn radius across both ski types falls below 125 m) and turn end (when mean turn radius across both ski types exceeds 125 m).

Local effects within the steep section

Within $Section_{STEEP}$ SKI_{WLH} caused an average reduction in E_{KIN} of ~3% for both skiers. Locally, this reduction was sometimes even larger. A maximal reduction in E_{KIN} (~−7.0%) was found during the sharp right turn at gate 2 for skier B. Within this specific subsection, the terrain was the steepest and turn radius was the smallest across the entire course. These findings illustrate the extent of the equipment-induced E_{KIN} reduction can—locally—reach quite substantial magnitudes that are comparable to the ones achieved by course setting interventions.[5 6 14]

For skier B, the local reduction in E_{KIN} during the sharp right turn at gate 2 was explained with a significant correlation between speed reduction and F_F, indicating that the loss in speed was mainly a result of higher ski–snow friction. An additional postanalysis from gate 1 to turn end after gate 2 found no difference in the CoM trajectories and turn radii as long as the skiers were turning (turn radius smaller than 125 m), neither between SKI_{WLH} and SKI_{REF} within the same skier, nor between the skiers. Hence, it is reasonable that the differences in the skier's response to the equipment intervention at gate 2 are most likely not a result of different trajectories, but rather due to differences in the ski–snow interaction.

Explanation of the observed local effects in F_F

The analysis of how the observed effects in F_F can be explained by variables related to the ski–snow interaction revealed that the differences in $Coeff_F$ contributed to a greater extent to the differences in F_F, than F_{GRF}. Hence, even the most extreme ski prototype (SKI_{WLH}) might not change the skier's movement patterns such that F_{GRF} is substantially affected, but changes how the skis interact with the snow. For skier B the increase in $Coeff_F$ and, therefore, in F_F seem to start early during the initiation phase of the turn (figure 4), and might be explained by an increased skidding prior to gate passage, as already observed for slalom skiing.[20] For skier A the increase in $Coeff_F$ was delayed and had a different pattern (figure 4).

Ski geometry and standing height in the context of injury prevention

High speed and, therefore, high E_{KIN} have several aspects that might influence the risk of severe traumatic injuries in super-G and DH.

First, in fall or crash situations, speed is a crucial factor, since the energy that is dissipated by forces during the impact increases with speed by the power of 2. In this context, the observed equipment-induced reduction in E_{KIN}/speed would theoretically lead to the same per cent wise reduction in the impulse (force over time) that acts in impact situations. Restated, a 3–7% local reduction in E_{KIN} would result in a reduction of the impact forces by 3–7% if the impact process time is held constant. However, it has to be pointed out that such a preventative gain can only be achieved when skiing on the most extreme ski prototype (ie, varying in width, standing height and length) and probably only within steep terrain, particularly if course setting causes small turn radii.

Second, anticipation and adaptation time within demanding course sections decrease with increasing E_{KIN}/speed, which plausibly results in a higher risk for technical and tactical mistakes.[3] Thus, a reduction in speed would give athletes more time to prepare for difficult course sections (eg, jumps, rough terrain transitions or turns) and make appropriate technical and/or tactical decisions. However, the observed reduction in speed in this study would only lead to marginal changes in preparation and adaption time. Given that an athlete skis with the average speed of $Section_{STEEP}$ (26.4 m/s) and oversees the upcoming course 20 m at a time, the observed equipment-induced reduction in speed would increase adaptation time by only 1/100–3/100 s. Hence, the preventative gain regarding this aspect is limited.

Third, increased E_{KIN}/speed is known to increase jump distance and airtime and might result in severe consequences in case the skier makes mistakes at the take-off.[3 4 21 22] Concerning this aspect, the current study findings indicate that only if a jump is located directly within or after a steep section skis modified in length, width and standing height would markedly reduce E_{KIN}/speed. In these situations, a ~3% reduction in E_{KIN}/speed would reduce jump distance and air time by ~0.5 m and ~2/100 s, depending on the shape of the jump.[3 4] Since many severe injuries are known to occur at jumps,[23] this reduction—even though it is small—might serve as a certain preventative gain to protect the athlete's health.

Compared with the magnitude of the E_{KIN} reduction, which might be achieved by course-related measures,[5 6 14] the equipment-induced 3% reduction in E_{KIN} in steep terrain and, therefore, the changes in preparation and adaption time to course features and the changes in jump distance and airtime seem to be rather small. However, by a smart combination with course-related and terrain-related measures, these small effects might become more relevant. Future studies should assess combined preventative measures including equipment and course setting modifications and investigate their effect on E_{KIN}/speed. Knowing that only the most extreme equipment modification showed a preventative effect with respect to E_{KIN}, and considering that the athletes reported a delayed reaction in general and reduced rebound in the second part of the turn for SKI_{WLH} and SKI_{WH}, ski ability and external attractiveness of the sport have to be considered. Benefits and costs must be balanced from an implementation point of view.

Methodological considerations

Since the study suffers from the small sample size and the limited number of repetitions per ski, the findings need to be interpreted with caution. Nevertheless, at this early stage of knowledge on injury prevention measures in DH and super-G, the new technology applied to top-level athletes in the current study might provide insights in the general mechanisms of ski–snow interaction and the effect of modified equipment in the context of injury prevention. Hence, this study might serve as guidance for future studies in a field where previously no scientific knowledge was available.

CONCLUSION

Recent studies suggested that measures to prevent injuries in super-G and DH should aim at reducing speed and E_{KIN} at spots where skiers are likely to crash. This is the first scientific study assessing equipment-related measures to reduce speed and E_{KIN} in DH. The study revealed that a simultaneous decrease in ski width and standing height and an increase in ski length reduces E_{KIN} by 3%, but within steep terrain only. Locally, even larger E_{KIN} reductions of up to 7% were observed. This indicates that an equipment-induced reduction of E_{KIN}/speed is feasible and can be considered an efficient way to increase the athlete's safety in steep terrain. However, it must be stated that the preventative gain from modified DH skis is limited compared with other external preventative measures, such as course setting. Therefore, effective prevention strategies in DH should involve several different preventative measures that aim to radically slow down skiers at locations where crashes are likely to occur.

What are the findings?

- This study investigates for the first time the influence of ski equipment-related preventative measures (ski, width, standing height, ski length) on the risk factors kinetic energy and speed in downhill (DH).
- It adds more detailed insights into how ski geometry and standing height influence kinetic energy within an entire DH course.

How might it impact on clinical practice in the future?

- In steep terrain, longer skis with decreased width and standing height reduce average kinetic energy by ~3%. Locally, the magnitudes of energy reduction were even larger (up to ~7%).
- Speed and kinetic energy of the skier determine to a large extent the impact forces during fall and crash situations. Therefore, the observed equipment-induced reduction in kinetic energy can be considered an effective way to improve the athletes' safety, although compared with other external interventions, the preventative gain of modified DH skis is rather small.

Contributors JK, JS and EM conceptualised and coordinated the study and its design. JK and MG conducted the data collection. MG conducted the data processing and parameter calculation. MG and JS analysed the data. All authors contributed to the intellectual content, writing of the manuscript and approved its content.

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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.

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SUPPLEMENTARY MATERIAL

Spatial normalization of time series data

To compare time series data for speed, E_{KIN}, F_{GRF}, F_F and $Coeff_F$, parameters were not time normalized from start to end of turns (which is usual for analysis in slalom and giant slalom,[1-3] but causes a certain bias between fast and slow skiers when the analysed sections are long, as it is typical for super-G and downhill); instead they were expressed as the distance from start to the instantaneous position of the skier along the course. Based on all measured skier trajectories and a geometrical approach,[4] an average trajectory was calculated from start to finish line. Each 0.3m along the average trajectory, a virtual plane was spanned normal to the average trajectory and was intersected with each of the single trajectories.[5] At each intersection point, the corresponding time series values for speed, E_{KIN}, F_{GRF}, F_F and $Coeff_F$ were interpolated and stored as a function of the distance from start along the average trajectory to the instantaneous position on the race track. This approach removes any bias of time shift in the time series data and allows comparing the parameters at the corresponding locations. In the figures, instantaneous parameter mean and standard error were plotted in function of distance from start. Distance from start was indicated with gate passage locations.

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