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

Matthias Gilgien,1 Jörg Spöri,2 Josef Kröll,2 Erich Müller2

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 (EKIN) 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. EKIN, speed, friction force (FF), ground reaction force (FGRF) and ski–snow friction coefficient (CoeffF) 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 EKIN by ~3%. Locally, even larger reductions of EKIN were observed (up to 7%). These local decreases in EKIN were mainly explainable by higher FF. Moreover, CoeffF differences seem of greater importance for explaining local FF differences than the differences in FGRF.

Conclusions Knowing that increased speed and EKIN likely lead to increased forces in fall/crash situations, the observed equipment-induced reduction in EKIN 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.3 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.1 4 Furthermore, high speed and, therefore, high kinetic energy (EKIN=1/2×mass×speed2) are likely to increase the forces that occur at the impact in fall or crash situations.3 Consequently, reducing EKIN 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 EKIN 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 EKIN/speed, as was hypothesised by expert stakeholders of the WC ski racing community. Yet to date, scientific knowledge on DH is very limited,3 5 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 EKIN 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), 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. EKIN, speed, ski–snow friction force (FF), ground reaction force (FGRF) and ski–snow friction coefficient (CoeffF) were calculated and analysed in dependency of the used skis.

Conclusions Knowing that increased speed and EKIN likely lead to increased forces in fall/crash situations, the observed equipment-induced reduction in EKIN can be considered a reasonable measure to improve athlete safety, even though the achieved preventative gains are rather small and limited to steep terrain.
steep and turning (Section$\text{STEEP}$), the second section was flat and less turning (Section$\text{FLAT}$; figure 1). The analysis for Section$\text{STEEP}$ started at the first gate where skiers reached 19.9 m/s and ended at gate number 9. The analysis of Section$\text{FLAT}$ 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.56 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.6 16 Skier speed, turn radius and $E_{\text{KIN}}$ were derived from the CoM position (measurement-system accuracy: 0.1 m).12 Ground reaction force (F$_\text{GFR}$) and ski–snow friction force (F$_\text{F}$) 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$_\text{GFR}$; 42N for F$_\text{F}$).17 The ski–snow friction coefficient (Coeff$_\text{F}$) was calculated as the coefficient of F$_\text{F}$ and F$_\text{GFR}$. To compare the time series data of speed, turn radius, $E_{\text{KIN}}$, F$_\text{GFR}$, F$_\text{F}$ and Coeff$_\text{F}$, 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$\text{STEEP}$ and Section$\text{FLAT}$ separately. For each run of each skier and each ski, $E_{\text{KIN}}$ averages of the Section$\text{STEEP}$ and Section$\text{FLAT}$ were calculated. Based on these single $E_{\text{KIN}}$ section averages, participant mean±SD values were computed for all tested skis. In addition, $E_{\text{KIN}}$ 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 $E_{\text{KIN}}$ difference between SKIREF and each ski type was calculated. 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 $E_{\text{KIN}}$ seemed to be the greatest was defined. Within this subsection (the sharp right turn at gate 2), the relation between $E_{\text{KIN}}$ and the $E_{\text{KIN}}$ explanatory parameters were investigated by the use of: (1) Spearman’s rank correlation coefficients between the $\text{WLH}SKI_{\text{WLH}}$–$SKI_{\text{REF}}$ differences in speed and the $\text{WLH}SKI_{\text{WLH}}$–$SKI_{\text{REF}}$ differences in F$_\text{F}$; and (2) a multiple

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SKIREF</th>
<th>SKIWH</th>
<th>SKIH</th>
<th>SKIW</th>
<th>SKIWH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (mm)</td>
<td>69</td>
<td>65</td>
<td>69</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Standing height (mm)</td>
<td>50</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>216</td>
<td>216</td>
<td>220</td>
<td>220</td>
<td>220</td>
</tr>
</tbody>
</table>

*SKIREF represents the original DH racing skis according to the FIS equipment rules valid until Winter Season 2011/2012.*

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Entire course</th>
<th>Section$\text{STEEP}$</th>
<th>Section$\text{FLAT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course length (m)</td>
<td>1302</td>
<td>1257</td>
<td>1347</td>
</tr>
<tr>
<td>Vertical drop (m)</td>
<td>402</td>
<td>402</td>
<td>402</td>
</tr>
<tr>
<td>Number of gates ( )</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Mean run time (s)</td>
<td>50.0</td>
<td>50.4</td>
<td>52.0</td>
</tr>
<tr>
<td>Median terrain inclination (°)</td>
<td>−23</td>
<td>−23</td>
<td>−15</td>
</tr>
<tr>
<td>Median gate distance (m)</td>
<td>84.23</td>
<td>84.23</td>
<td>84.23</td>
</tr>
<tr>
<td>Median horizontal gate distance (m)</td>
<td>35.65</td>
<td>35.65</td>
<td>35.65</td>
</tr>
<tr>
<td>Mean direction change from gate to gate (°)</td>
<td>23</td>
<td>23</td>
<td>11</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Section$\text{STEEP}$</th>
<th>Section$\text{FLAT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{KIN}}$ (J/BW)</td>
<td>31.1</td>
<td>30.6</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>24.7</td>
<td>24.5</td>
</tr>
</tbody>
</table>

*Figure 1* Map of the course with gates, gate numbers and skier trajectories. The boundaries of the steep section (Section$\text{STEEP}$) and the flat section (Section$\text{FLAT}$) and the sharp right turn at gate 2 are indicated with arrows.
regression analysis assessing the contribution of differences in CoefF and in F GRF to explain the local differences in F F between SKIREF and SKIWLH.

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 EKIN within SectionSTEEP and SectionFLAT for both skiers. Figure 2 illustrates the instantaneous EKIN (i.e., its mean±SE from start of SectionSTEEP to end of SectionFLAT for both skiers using SKIREF). It can be visually observed that EKIN/speed was higher in SectionFLAT than SectionSTEEP and that instantaneous differences between the skiers were present at various locations of the course.

Differences in EKIN between the tested skis within specific sections of the course

The results reporting the EKIN section average differences between the tested skis are shown in Table 4. The one-way ANOVA analysis was significant for both skiers for SectionSTEEP but not for SectionFLAT, indicating that the equipment intervention did not have an effect on EKIN/speed in SectionFLAT. At the pairwise comparisons (right side of table 4), a difference is negative if the modified skis showed smaller EKIN mean values than SKIREF. The only ski prototypes that caused a statistically significant reduction in EKIN/speed compared with SKIREF was SKIWLH. This finding was independently observed for both skiers in SectionSTEEP 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 EKIN/speed difference with respect to SKIREF was not significantly different between skiers but was significantly smaller in SectionSTEEP (0.07±0.03 m/s) than in SectionFLAT (0.21±0.08 m/s).

Differences in EKIN between SKIWLH and SKIREF in SectionSTEEP

Figure 3 illustrates the instantaneous differences in EKIN between SKIREF and SKIWLH for skiers A and B within SectionSTEEP.
DISCUSSION

The main findings of the study were that no difference between the tested skis on average $E_{KIN}$ in Section\textsc{Flat} were observed, but SKI\textsc{WLH} caused a $\sim 3\%$ $E_{KIN}$ reduction for both skiers in Section\textsc{Steep} compared with SKI\textsc{REF}. No other differences between SKI\textsc{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 ($\sim 7.0\%$ for skier B; $\sim 3.6\%$ 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 $\text{Coeff}_{F}$.

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\textsc{Steep} than in Section\textsc{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.\(^7\)\(^6\)

Comparing the individual progressions of $E_{KIN}$/speed between skiers A and B when skiing on SKI\textsc{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\textsc{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\textsc{Steep} where the significant speed reductions were found between SKI\textsc{WLH} and SKI\textsc{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\textsc{REF} in Section\textsc{Flat}. However, a significant reduction of $\sim 3\%$ in $E_{KIN}$ was found for the prototype with all three parameters altered (SKI\textsc{WLH}) in Section\textsc{Steep} (table 4). Furthermore, postanalysis for Section\textsc{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\textsc{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 ($\text{Coeff}_{F}$) 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\textsc{REF}) and SKI\textsc{WLH} during the sharp right turn at gate 2

<table>
<thead>
<tr>
<th>Predictors of $F_{F}$</th>
<th>$\beta$-weight</th>
<th>$p$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skier A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coeff$_{F}$</td>
<td>1.011</td>
<td>0.004</td>
</tr>
<tr>
<td>$F_{GRF}$</td>
<td>0.123</td>
<td>0.011</td>
</tr>
<tr>
<td>Skier B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coeff$_{F}$</td>
<td>0.944</td>
<td>0.006</td>
</tr>
<tr>
<td>$F_{GRF}$</td>
<td>$-0.320$</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Model for skier A: adjusted $R^2=0.002$; $p=0.012$.
Model for skier B: adjusted $R^2=0.012$; $p=0.010$.

Local effects within the steep section
Within SectionSTEEP SKIWLH caused an average reduction in $E_{\text{kin}}$ of $\sim3\%$ for both skiers. Locally, this reduction was sometimes even larger. A maximal reduction in $E_{\text{kin}}$ ($\sim-7.0\%$) 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 $E_{\text{kin}}$ reduction can—locally—reach quite substantial magnitudes that are comparable to the ones achieved by course setting interventions.\textsuperscript{5, 4}

For skier B, the local reduction in $E_{\text{kin}}$ during the sharp right turn at gate 2 was explained with a significant correlation between speed reduction and $F_R$, 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 SKIWLH and SKIREF 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 $\text{Coeff}_F$ contributed to a greater extent to the differences in $F_R$ than $F_{\text{GRF}}$. Hence, even the most extreme ski prototype (SKIWLH) might not change the skier’s movement patterns such that $F_{\text{GRF}}$ is substantially affected, but changes how the skis interact with the snow. For skier B the increase in $\text{Coeff}_F$ 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.\textsuperscript{20} For skier A the increase in $\text{Coeff}_F$ 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 $E_{\text{kin}}$ 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 $E_{\text{kin}}$/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 $E_{\text{kin}}$ 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, par-
ticularly if course setting causes small turn radii.

Second, anticipation and adaptation time within demanding
course sections decrease with increasing $E_{\text{kin}}$/speed, which
plausibly results in a higher risk for technical and tactical mis-
takes.

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 adaptation time. Given that an athlete skis with the average
speed of Section$^{\text{STEEP}}$ (26.4 m/s) and oversees the upcoming
course 20 m at a time, the observed equipment-induced reduc-
tion in speed would increase adaptation time by only 1/100–3/
100 s. Hence, the preventative gain regarding this aspect is
limited.

Third, increased $E_{\text{kin}}$/speed is known to increase jump dis-
tance and airtime and might result in severe consequences in
case the skier makes mistakes at the take-off. 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 mark-
edly reduce $E_{\text{kin}}$/speed. In these situations, a $\sim 3\%$ reduction in $E_{\text{kin}}$/speed would reduce jump distance and air time by $\sim 0.5$ m
and $\sim 2/100$ s, depending on the shape of the jump. Since many severe injuries are known to occur at jumps, this reduc-
tion—even though it is small—might serve as a certain preventa-
tive gain to protect the athlete’s health.

Compared with the magnitude of the $E_{\text{kin}}$ reduction, which might be achieved by course-related measures, the equipment-induced $3\%$ reduction in $E_{\text{kin}}$ in steep terrain and, therefore, the changes in preparation and adaptation 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 $E_{\text{kin}}$/speed. Knowing that only the most extreme equip-
ment modification showed a preventative effect with respect to
$E_{\text{kin}}$, and considering that the athletes reported a delayed
reaction in general and reduced rebound in the second part of the turn for SKI$^{\text{W1H}}$ and SKI$^{\text{W1H}}$, ski ability and exter-
nal 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-

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.

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