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Mechanics of turning and jumping and skier speed are associated with injury risk in men's World Cup alpine skiing: a comparison between the competition disciplines

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ABSTRACT

Background/aim In alpine ski racing, there is limited information about skiers' mechanical characteristics and their relation to injury risk, in particular for World Cup (WC) competitions. Hence, current findings from epidemiological and qualitative research cannot be linked to skiers' mechanics. This study was undertaken to investigate whether recently reported differences in numbers of injuries per 1000 runs for competition disciplines can be explained by differences in the skiers' mechanics.

Methods During seven giant slalom, four super-G and five downhill WC competitions, mechanical characteristics of a forerunner were captured using differential global navigation satellite technology and a precise terrain surface model. Finally, the discipline-specific skiers' mechanics were compared with the respective number of injuries per hour skiing.

Results While the number of injuries per hour skiing was approximately equal for all disciplines, kinetic energy, impulse, run time, turn radius and turn speed were significantly different and increased from giant slalom to super-G and downhill. Turn ground reaction forces were largest for giant slalom, followed by super-G and downhill. The number of jumps was doubled from super-G to downhill.

Conclusions Associating the number of injuries per hour in WC skiing with skiers' mechanical characteristics, injuries in super-G and downhill seem to be related to increased speed and jumps, while injuries in giant slalom may be related to high loads in turning. The reported differences in the number of injuries per 1000 runs might be explained by a bias in total exposure time per run and thus potentially by emerged fatigue.

INTRODUCTION

Competitive alpine skiing is considered to be a sport with a high injury risk.[1 2] Injury rates per competition season and per 100 World Cup (WC) athletes were reported to be 36.7, with the knee being the most frequently affected body part.[1 3] Injury rates were found to be dependent on the discipline (for men/women: slalom: 7.5/1.5 injuries per 1000 runs, giant slalom: 12.8/5.1, super-G: 14.5/7.7 and downhill: 19.3/13.9).[1] Based on these findings, it was hypothesised that injury risk increases with speed.[1] In a qualitative study based on expert stakeholders' opinions, high speed was also considered as a key injury risk factor leading to large impact energies and high turn forces.[2] However, as recently illustrated, speed might not be the only factor related to injury risk: out-of-balance situations while turning or landing and fatigue might be other important factors increasing injury risk.[4 5] Moreover, a recent experimental study in giant slalom showed that speed, the risk of out-of-balance situations, turn force and probably fatigue might be dependent on course setting.[6] Hence, these factors might serve as additional explanatory approaches for the differences in the number of injuries per 1000 runs among the disciplines.

Despite the large body of knowledge about injury rates[1 3 7 8] and injury risk factors,[2 4–6 9] little is known about how the mechanics of turning and jumping, skier speed and fatigue ('mechanical characteristics' of skiing) influence injury risk during WC alpine competitions. Consequently, we aimed to quantify these important skiing-related variables for the disciplines giant slalom, super-G and downhill. We also investigated whether these variables could explain the differences in the number of injuries per 1000 runs among the disciplines.

METHODS

Measurement protocol

Seven WC giant slalom races (14 runs in total at Sölden, Beaver Creek, Adelboden, Hinterstoder, Crans Montana), four super-G races (4 runs in total at Kitzbühel, Hinterstoder, Crans Montana) and five downhill races (16 runs in total at Lake Louise, Beaver Creek, Wengen, Kitzbühel, Åre) were monitored during the WC season 2010/2011 and 2011/2012. In the giant slalom discipline, each single run was included in the analysis. In downhill official competition training runs were also used. If several downhill runs were measured in one race location, they were treated as repeated measures in the analysis. At each race, one official forerunner (skier who precedes the racers to test the track) was equipped to collect data for this study. All forerunners were former WC or current European Cup racers.

Data collection methodology

The forerunner's trajectory was captured using a differential global navigation satellite system (dGNSS). The dGNSS antenna (G5Ant-2AT1, Antcom, USA) was mounted on the skier's helmet and a GPS/GLONASS dual frequency (L1/L2) receiver (alpha-G3T, Javad, USA) recorded position signals at 50 Hz. The receiver was carried in a

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small cushioned backpack. Differential position solutions of the skier trajectory were computed using the data from two base stations (antennas (GrAnt-G3T, Javad, USA) and alpha-G3T receivers (Javad, USA) and the geodetic postprocessing software GrafNav (NovAtel Inc, Canada).

The snow surface geomorphology was captured using static dGNSS (alpha-G3T receivers with GrAnt-G3T antenna (Javad, USA) and Leica TPS 1230+ (Leica Geosystems AG, Switzerland)). Using the surveyed snow surface points (in average 0.3 points/m^2 were captured), a digital terrain model (DTM) was computed by Delaunay triangulation[10] and smoothing with bi-cubic spline functions.[11 12]

Computing skier mechanics—turns, jumps, speed

The antenna trajectory was spline filtered[13 14] and was used together with the DTM as input parameters for a mechanical model[13 14] from which the instantaneous skier turn radius, speed, air drag force (F_D) and ground reaction force (F_{GRF}) were reconstructed. The applied data capture and parameter reconstruction method was validated against reference methods for position, speed and forces.[13 14] Using speed of the entire runs and the skier's mass, the skier kinetic energy (E_{kin}) was computed. E_{kin} was normalised for the skier's mass and expressed in BW·m. The impulses of F_{GRF} and F_D were calculated for the entire race and added (I_{GRF+D}) as shown in equation 1. I_{GRF+D} might account for the major part of the processes causing fatigue. The race time was measured with the official race timing system.

The jump frequency per race (J_f), airtime (J_t) and distance (J_d) per jump were determined from the skier trajectory and the DTM. The time of takeoff was determined from the distance over ground (figure 1) and the touchdown from the peak of the vertical acceleration. J_d and J_t were computed from the spatial and temporal difference between takeoff and touchdown locations.

$$I_{GRF+D} = \int_{\text{Start}}^{\text{Finish}} F_{GRF}dt + \int_{\text{Start}}^{\text{Finish}} F_D dt \qquad (1)$$

Epidemiological injury data (number of injuries per 1000 runs) from the FIS ISS injury surveillance system[1] were used to compute the number of injuries per hour skiing. Exposure time was defined as the average race time per discipline and was calculated as the mean of all race medians involving all racers who finished the race. The data for the exposure time analysis were taken from the fis-ski.com webpage and represented the same two seasons (2006/2007 and 2007/2008) in which the injury data were collected. Finally, the number of injuries per hour skiing (average run time×number of runs in WC races) were computed for each discipline and were compared with the skier's mechanical characteristics.

Statistical analysis

For E_{kin}, I_{GRF+D}, run time, J_f, J_t and J_d, the mean and SD were calculated within each discipline and compared as a percentage of the downhill values. The medians of each discipline were compared using a Kruskal-Wallis test (α=0.01). The distributions between and within disciplines were illustrated in histograms for speed, turn radius and F_{GRF}. Straight skiing was defined by a minimum turn radius of 125 m for all disciplines. To compare turn characteristics between the disciplines, the phases with substantial direction change were defined and analysed based on a maximal turn radius criterion: 30 m in giant slalom[6] and proportional criteria for super-G (75 m) and downhill (125 m). The mean of the turn means was calculated for turn speed, turn F_{GRF} and turn radius within each discipline. The extreme values (minimum for turn radius, maximum for turn speed and F_{GRF}) were calculated for each turn and the values of the turns with 10% most extreme values were averaged within each discipline. The median of each discipline was compared using a Kruskal-Wallis test (α=0.01).

RESULTS

The number of injuries per hour skiing are given in table 1. The injury rate was highest for giant slalom, followed by super-G, downhill and slalom. While the differences between downhill, super-G and giant slalom were less than 2%, slalom had an 18% lower injury rate than downhill.

The distributions within and between disciplines for turn speed, turn radius and F_{GRF} are shown in figure 2. For F_{GRF}, distributions between disciplines were similar, with the largest variance for giant slalom and the smallest for downhill. Turn speed and turn radius had larger distribution differences between disciplines. Downhill had the largest mean turn radius, while giant slalom had the smallest mean turn radius. Straight skiing (turn radius of >125 m) occurred for approximately 45% of the time in downhill, 20% in super-G and 7% in giant slalom.

Skier mechanical characteristics specific for turning are presented in table 2. For the turns, limited by maximal turn radii of 30 m (giant slalom), 75 m (super-G) and 125 m (downhill), the mean and extreme values of turn speed, turn radius and turn F_{GRF} are presented. While turn speed and turn radius mean and extreme values increased from giant slalom to super-G and downhill, they decreased for turn F_{GRF}. The medians were significantly different (α=0.01) between disciplines for all parameters.

The mean, SD and percentage of downhill values for E_{kin}, I_{GRF+D}, run time and jump characteristics for the entire runs are given in table 3. All mean values were largest for downhill, followed by super-G and giant slalom for all parameters. Super-G consisted of about half the number of jumps compared with downhill, while giant slalom had none. The jumps were about 20% shorter in super-G compared with downhill, but airtime was reduced by only 6%. The medians were significantly different (α=0.01) between disciplines for all parameters except the jump parameters.

Associating skiers' mechanical characteristics with injury rates, figure 3 shows the mean and extreme values of turn speed, turn radius and turn F_{GRF} compared with the injury rates. Injuries per hour skiing were similar between disciplines, while injuries per 1000 runs and mean and extreme values increased from giant slalom to super-G and downhill for turn speed, turn radius and for kinetic energy of the entire run. The difference in turn radius mean and minimum was substantial between giant slalom and the speed disciplines. F_{GRF} in turns increased from downhill to super-G and giant slalom.

DISCUSSION

The main findings of this study were that (1) the number of injuries per hour skiing was similar for giant slalom, super-G and downhill; (2) downhill consisted of 45% straight skiing, super-G of 20% and giant slalom of 7%; (3) in turns, turn speed and turn radius were largest in downhill, followed by super-G and giant slalom, while the ranking was inverse for F_{GRF}; (4) kinetic energy, impulse due to F_{GRF} and air drag and run time were largest for downhill, followed by super-G and

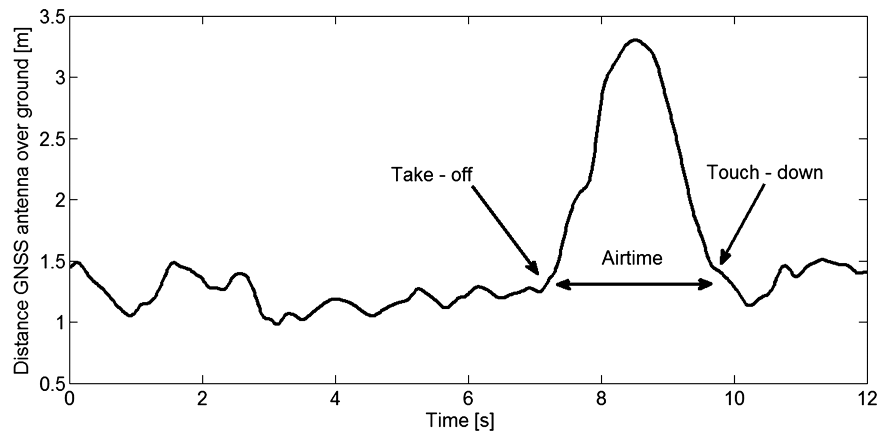

Figure 1 Altitude over ground of the global navigation satellite system antenna trajectory for a 12 s long section including a jump during a super-G race. Takeoff, touchdown and airtime of the jump are indicated with arrows.

giant slalom and (5) jump frequency, jump length and airtime were larger for downhill than for super-G.

Mechanics of turning

It has recently been found that many injuries occur while turning, without falling or being the result of a crash.[4] Figure 2 shows that skiers are turning for approximately 55% of the time in downhill, 80% in super-G and 93% in giant slalom. Moreover, it was shown that small turn radii might be related to an increased injury risk in giant slalom since they provoke the skiers to use their full backward and inward leaning capacities, and thus skiers have less buffer if an additional factor causes an out-of-balance situation.[6] Out-of-balance situations themselves are known to be a critical part of typical injury mechanisms, such as the 'slip-catch' and 'dynamic snowplow'[4 5 13]. Comparing the mean and minimal turn radii between disciplines from figure 3 and table 3, it is evident that giant slalom has substantially smaller turn radii than super-G and downhill. Additional analysis of the data showed that the radial component is the main contributor to the increased F_{GRF} in giant slalom. Thus, the combination of small turn radii and speed leads to larger mean and maximum F_{GRF} in giant slalom compared with super-G and downhill. Furthermore, in giant slalom, skiers' balance might be challenged simultaneously by small turn radii and high forces. Measures to prevent injuries in giant slalom should, therefore, focus on speed and turn radius. Suitable tools might be course setting and equipment. Furthermore, giant slalom includes a larger number of turns (52.0±3.5) compared with super-G (40.0±3.5) and downhill. Hence, skiers have to find balance in turning more frequently in a run and thus might be more often susceptible to balance-related mistakes in turn initiations.

Speed and kinetic energy

Speed, in general, is considered a major injury risk factor in competitive alpine skiing.[1 2] It has been hypothesised that the differences in speed might be the reason for the higher numbers of injuries per 1000 runs in the speed disciplines.[1] Comparing the number of injuries per hour skiing and kinetic energy in figure 3, no direct relationship is apparent, since speed increased from giant slalom to super-G and downhill while the injury rates were almost constant across the disciplines. This finding indicates that speed might not be the sole factor explaining the differences in injury rates between disciplines. Nevertheless, speed might have several major impacts on injury risk, especially in downhill and super-G. In technically demanding sections (eg, jumps, rough terrain and turns), anticipation and adaptation time decrease with speed and mistakes might be more likely to occur. Furthermore, for a given jump, jump distance and airtime increase with speed and a mistake at takeoff might have more severe consequences. In crash situations, speed has a significant effect, since the energy which is dissipated in an impact increases with speed by the power of 2 (E_{kin}=½·mass·speed^2) and E_{kin} is almost doubled from giant slalom to downhill. The forces occurring in a crash impact are dependent on the initial kinetic energy and the timespan of the energy-dissipation process. Safety barriers are, therefore, built so that they can give way to a certain extent in order to increase the time of the impact process and thus decrease the impact forces. Hence, the functionality[15 16] and positioning of protective barriers are highly important in speed disciplines. Measures to prevent injuries in super-G and downhill should aim at reducing speed at spots where skiers are likely to crash. Since turn forces in downhill are generally lower compared with giant slalom and super-G, it might be reasonable to use course setting to radically slow down skiers at locations where crashes are likely to occur.

Table 1 Calculation of the number of injuries per hour skiing

Discipline	Number of injuries	Number of runs	Mean run time (s)	Exposure time (h)	Incidence (injuries/hour)	Percentage of downhill*
Slalom	14	1864	53.00	27.44	0.510	81.7
Giant slalom	14	1090	75.40	22.83	0.613	98.3
Super-G	9	620	83.38	14.36	0.627	100.4
Downhill	25	1292	111.62	40.06	0.624	100.0

The number of injuries and the number of runs were taken from Florenes *et al.*[1] The number of injuries per hour skiing (incidence) was calculated as the number of injuries divided by the exposure time.
*Downhill is 100% for the respective measures.

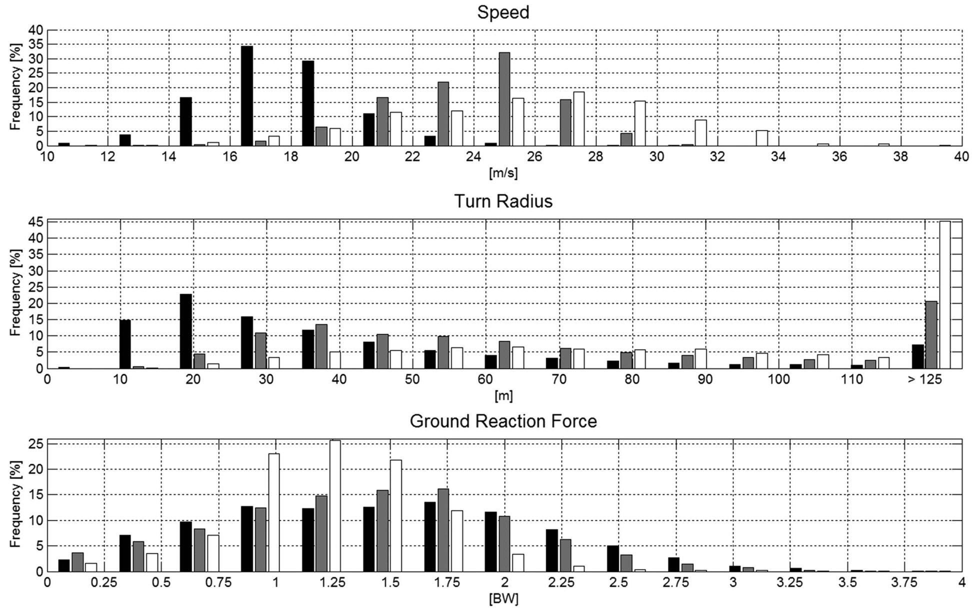

Figure 2 Histograms for speed, turn radius and ground reaction force. Giant slalom is shown in black, super-G in grey and downhill in white.

Fatigue

Fatigue is an injury risk factor.[2] A recent study showed that most injuries occur during the last fourth of a race.[4] It is further known that fatigue has a negative effect on balance[17 18] and thus fatigued athletes might be more susceptible to out-of-balance situations and injuries.[6] Since fatigue cannot be measured directly, in the current study, race time and impulse were calculated as approximations of the work load over the entire run. I_{GRF+D} per run showed an increase from giant slalom to super-G and downhill along with an increase in the number of injuries per 1000 runs. Analyses of the causes for the differences in impulse between disciplines revealed that run time contributed to a larger extent to the impulse than the forces. Consequently, the fatigue-related parameter impulse is strongly linked with exposure time. Exposure time (and fatigue) seems to explain the increased injury rate per 1000 runs for the speed disciplines to a large extent. Two seasons of epidemiological data are a relatively small amount for the computation of injury rates, but there is a trend between run time and the number of injuries per 1000 runs. If epidemiological studies could pinpoint when accidents occur in a race for the respective disciplines, the role of fatigue could probably be clarified.

Jumps

Jumps are considered to contribute to high injury rates.[2] The number of jumps in downhill is nearly double than that in super-G. However, no epidemiological study has ever pinpointed the number of injuries occurring at jumps in the respective disciplines. Hence, it has not been possible as yet to relate jump characteristics to injury risk.

An imbalance at the jump takeoff can lead to an angular momentum during the time the skier is airborne. Since the angular momentum is only influenced by air drag as long as the skier is airborne, the time until landing is critical. A longer airtime leads to a larger rotation angle and a more critical body position at landing. In the current study, it was found that flight distance was 21% shorter in super-G compared with downhill, while airtime was only 6% shorter in super-G compared with downhill. This finding leads to the conclusion that an angular momentum during airtime can also lead to large rotation angles

Table 2 Turn characteristics: mean values, extreme values and percentage of downhill for the disciplines giant slalom, super-G and downhill

		Mean and extreme values for turns			Percentage of downhill*	
		Giant slalom	Super-G	Downhill	Giant slalom	Super-G
Turn speed (m/s)	Mean	17.32	22.7	24.0	72	95
	Max	22.2	28.3	32.3	69	88
Turn radius (m)	Mean	22.7	52.0	61.6	37	84
	Min	8.4	17.2	20.6	41	84
Turn F_{GRF} (BW)	Mean	2.02	1.58	1.43	141	110
	Max	3.16	2.79	2.59	122	108

*Downhill is 100% for the respective measures.
F_{GRF}, ground reaction force.

Table 3 Mean and SD values for disciplines giant slalom, super-G and downhill and as percentage of downhill for slalom, giant slalom and super-G

	Mean±SD in absolute values			Percentage of downhill*	
	Giant slalom	Super-G	Downhill	Giant slalom	Super-G
E_{kin} (BW m)	15.5±4.0	27.9±6.1	32.7±10.7	47	85
I_{GRF+D} (kBW s)	124.3±12.5	153.0±13.3	173.4±25.3	71	88
Run time (s)	77.4±5.2	92.9±9.7	121.4±17.7	64	76
Number of jumps/race	–	2.3±0.8	4.2±1.5	–	55
Jump length (m)	–	23.8±9.9	30.2±10.4	–	79
Jump airtime (s)	–	0.98±0.44	1.04±0.44	–	94

E_{kin}, skier kinetic energy.
*Downhill is 100% for the respective measures.

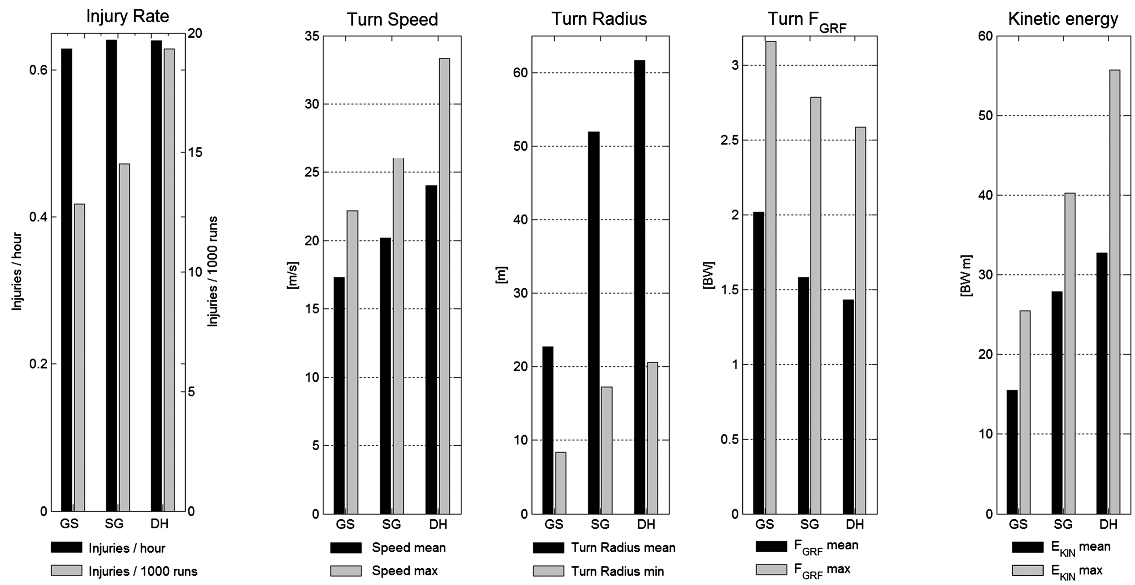

Figure 3 Comparison of injury rates (left graph), skiers' characteristics in turns (turn speed, turn radius and turn ground reaction force (F_{GRF}), in middle) and skiers' kinetic energy for entire runs. For injury rates, injuries per hour are shown in black and injuries per 1000 runs in grey. For skiers' mechanical characteristics, mean values are shown in black and extreme values in grey. The disciplines are abbreviated as: GS, giant slalom; SG, super-G; DH, downhill.

in super-G. Since many severe injuries[4] seem to occur at jumps, the mechanics of jumping and its relation to injury risk should be investigated in more detail.

LIMITATIONS

Measuring key skiing variables under competition conditions in WC alpine skiing adds valuable new perspectives to the investigation of injury risk factors. However, we acknowledge several limitations related to our methods.

First, the model for the computation of F_{GRF} does not capture the high frequency force components and, therefore, might underestimate the work load (impulse), in particular for giant slalom.

Second, for the computation of impulse, the method used does not account for body positions and their different costs. Consequently, the work load during straight gliding sections in downhill, where skiers are in a deep tuck position and likely are exposed to higher costs, might be underestimated compared with giant slalom, where skiers are in more extended body positions.

Third, the forerunners who captured the data for this study skied slightly slower than the WC skiers. The time difference between our forerunners and the median of all skiers who completed the run was 2.4±2.1% for giant slalom, 1.3±2.3% for super-G and 5.3±1.2% for downhill. Hence our data slightly underestimate the mechanical characteristics of a typical WC skier.

The study does not include female athletes. It remains, therefore, unknown if the differences in injury rate, expressed as the number of injuries per 1000 runs, between men and women are caused by differences in skier mechanics.

SUMMARY

This study showed that the disciplines in WC alpine skiing are approximately equally dangerous per time unit. In contrast, the skiers' mechanical characteristics were significantly different. Therefore, it is likely that the causes and mechanisms of injury are different for the specific disciplines. In super-G and downhill, injuries might be mainly related to higher speed and jumps, while injuries in the technical disciplines might be related to a combination of turn speed and turn radius resulting in high loads. Therefore, future epidemiological and qualitative studies should pinpoint types of injuries and injury mechanics in each discipline to facilitate suitable injury-prevention measures for the specific disciplines.

Another interesting finding of this study is the fact that the number of injuries per 1000 runs showed a similar increase (from giant slalom to downhill) to the parameters of race duration and impulse. Hence, the recently reported higher number of injuries per 1000 runs in downhill might not only be explained by speed but also by a bias of total exposure time and thus potentially by the development of fatigue.

What are the new findings?

- This is the first study to comprehensively quantify the mechanical characteristics of World Cup alpine skiing under real race conditions.
- World Cup alpine skiing is equally dangerous per unit time for the disciplines giant slalom, super-G and downhill.
- Injuries in giant slalom were linked to high loads in turning; injuries in downhill and super-G were linked to jumps and speed and the mechanical energy involved in crashing.
- Different injury rates in the different disciplines relate to exposure duration—the risk per unit time is comparable.

How might it impact on clinical practice in the near future?

- The quantification of World Cup ski racing mechanics might allow future studies to use the correct magnitude of skier mechanical characteristics.
- Injury prevention efforts are likely need to be discipline specific to address injury-specific risk factors.

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Competing interests None.

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.

REFERENCES

1 Florenes TW, Bere T, Nordsletten L, *et al*. Injuries among male and female World Cup alpine skiers. *Br J Sports Med* 2009;43:973–8.
2 Spörri J, Kröll J, Amesberger G, *et al*. Perceived key injury risk factors in World Cup alpine ski racing an explorative qualitative study with expert stakeholders. *Br J Sports Med* 2012;46:1059–64.
3 Florenes TW, Nordsletten L, Heir S, *et al*. Injuries among World Cup ski and snowboard athletes. *Scand J Med Sci Sports* 2012;22:58–66.
4 Bere T, Florenes TW, Krosshaug T, *et al*. A systematic video analysis of 69 injury cases in World Cup alpine skiing. *Scand J Med Sci Sports* 2013.
5 Bere T, Florenes TW, Krosshaug T, *et al*. Mechanisms of anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. *Am J Sports Med* 2011;39:1421–9.
6 Spörri J, Kröll J, Schwameder H, *et al*. Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *Br J Sports Med* 2012;46:1072–7.
7 Ekeland A, Nordsletten L. Equipment related injuries in skiing: recommendations. *Sports Med* 1994;17:283–7.
8 Pujol N, Blanchi M, Chambat P. The incidence of anterior cruciate ligament injuries among competitive alpine skiers: a 25-year investigation. *Am J Sports Med* 2007;35:1070–4.
9 Raschner C, Platzer H, Patterson C, *et al*. The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. *Br J Sports Med* 2012;46:1065–71.
10 de Berg M, Otfried C, van Kreveld M, *et al*. *Computational geometry: algorithms and applications*. Berlin: Springer Verlag, 2008:1–386.
11 Hugentobler M. *Terrain modelling with triangle based free-form surfaces*. Zürich, Switzerland: Universität Zurich, 2004.
12 Gilgien M, Reid R, Haugen P, *et al*. *A method to capture and model the geomorphology of snow surfaces for use in biomechanical investigations in snow sports. 2008 Jul 9;13th Annual Congress of the European College of Sport Science*. Lisboa, Portugal: European College of Sport Sciences, 2008:569.
13 Gilgien M, Spörri J, Kröll J, *et al*. *Speed as an injury risk factor in competitive alpine ski racing depends on events. 2012 Jul 4;17th Annual Congress of the European College of Sport Science*. Brugge, Belgium: European College of Sport Science, 2012:243.
14 Gilgien M, Spörri J, Chardonnens J, *et al*. Determination of external forces in alpine skiing using a differential global navigation satellite system. *Sensors* 2013;13:9821–35.
15 Petrone N, Ceolin F, Morandin T. Full scale impact testing of ski safety barriers using an instrumented anthropomorphic dummy. *Procedia Eng* 2010;2:2593–8.
16 Petrone N, Pollazzon C, Morandin T. *Structural behaviour of ski safety barriers during impacts of an instrumented dummy. The Engineering of Sport 7*. Paris: Springer, 2008:633–42.
17 Qu X, Nussbaum MA. Effects of external loads on balance control during upright stance: experimental results and model-based predictions. *Gait Posture* 2009;29:23–30.
18 Simoneau M, Begin F, Teasdale N. The effects of moderate fatigue on dynamic balance control and attentional demands. *J Neuroeng Rehabil* 2006;3:22.