Original Research

Course Setting as a Prevention Measure for Overuse Injuries of the Back in Alpine Ski Racing

A Kinematic and Kinetic Study of Giant Slalom and Slalom

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Background: A combination of frontal bending, lateral bending, and torsion in the loaded trunk has been suggested to be a mechanism leading to overuse injuries of the back in Alpine ski racing. However, there is limited knowledge about the effect of course setting on the aforementioned back-loading patterns.

Purpose: To investigate the effect of increased gate offset on the skier's overall trunk kinematics and the occurring ground-reaction forces and to compare these variables between the competition disciplines giant slalom (GS) and slalom (SL).

Study Design: Controlled laboratory study.

Methods: Ten top-level athletes were divided into GS and SL groups. Both groups performed a total of 240 GS and 240 SL turns at 2 different course settings. The overall trunk movement components (frontal bending, lateral bending, and torsion angle) were measured using 2 inertial measurement units fixed on the sacrum and sternum. Total ground-reaction forces were measured by pressure insoles.

Results: In SL, ground-reaction force peaks were significantly lower when the gate offset was increased, while in GS, no differences between course settings were observed. During the turn phase in which the highest spinal disc loading is expected to occur, the back-loading patterns in both GS and SL included a combination of frontal bending, lateral bending, and torsion in the loaded trunk. SL was characterized by shorter turns, lower frontal and lateral bending angles after gate passage, and a trend toward greater total ground-reaction force peaks compared with GS.

Conclusion: Course setting is a reasonable measure to reduce the skier's overall back loading in SL but not in GS. The distinct differences observed between GS and SL should be taken into account when defining discipline-specific prevention measures for back overuse injuries.

Clinical Relevance: To reduce the magnitude of the overall back loading, in SL, minimal gate offsets should be avoided. Prevention measures in GS might particularly need to control and/or reduce the magnitude of frontal and lateral bending in the loaded trunk, whereas prevention measures in SL might especially need to mitigate the short and high total ground-reaction force peaks.

Keywords: overuse injuries; spine; back pain; injury prevention; athletes; skiing

Overuse injuries of the back are known to be a frequent complaint among top athletes.[1,6,14,17] In the sport of Alpine ski racing, the athlete's back is reported to be the most affected body part for overuse injuries.[13] A pilot study assessing the overuse complaints of top-level slalom racers revealed that more than one-third of athletes (male, 33%; female, 41%) have a history of recurrent or chronic pain in the lower back since competing at the World Cup level.[31] Compared with an age-matched normal population, this proportion is considered to be remarkably high.[21,22] Even young competitive Alpine skiers demonstrate a significantly higher rate of anterior endplate lesions than nonathletic controls.[28] Furthermore, a direct relationship between structural deteriorations/abnormalities in the spine and a greater risk of developing low back pain at follow-up has been documented.[19,20,26]

In athletes, this prevalence of overuse injuries of the back might have different causes. First, a high incidence of mechanical overloading, in general, might lead to

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excessive and repetitive spinal loads that accumulate during the athletes' careers.[3,17] Additionally, sport-specific loading patterns might play a major role in the development of overuse injuries of the back. In several sports such as golf, tennis, gymnastics, or cricket, frontal bending (ie, forward flexion), lateral bending (ie, sideward flexion), and torsion in the trunk as well as high peak loads have been suggested to be major factors increasing the risk for overuse injuries of the back.[2,8,10,27] There is strong theoretical and empirical evidence that a combined occurrence of some or all of these factors increases spinal disc loading.[3,10,11,15,35,36]

Recently, a combination of frontal bending, lateral bending, and torsion in the trunk as well as high peak loads (up to 2.89 times the body weight) were shown to occur during carved ski turns.[33] These findings led to the recommendation that prevention measures in Alpine ski racing should aim to control and/or reduce the magnitude of frontal bending, lateral bending, and torsion in the trunk as well as the skier's overall loading.[33] However, based on current competition rules,[5] there is a broad range of possible course settings, and the effect of course setting on spinal disc loading is unclear. A deeper understanding of this effect is essential for the purpose of injury prevention. Furthermore, since the mechanical framework (ie, center of mass [COM] turn radius, COM turn speed), the skiing equipment used, and the gate clearance technique are markedly different between the competition disciplines of giant slalom (GS) and slalom (SL), it is not clear whether there are distinct, discipline-specific differences in the mechanisms leading to overuse injuries of the back.

Consequently, the current study aimed to (1) investigate the effect of increased gate offsets on the biomechanical variables related to spinal disc loading in GS and SL and (2) compare the aforementioned variables between these competition disciplines. With regard to the first aim, it was hypothesized that, in both disciplines, greater gate offsets increase the acting ground-reaction forces, as the skiers' turn radii are expected to be decreased because of more substantial changes of direction at equal vertical gate distances.[32] For the overall trunk movement components, no specific effect of altered gate offset was hypothesized. However, to conclusively judge whether the assessed course setting intervention has an effect on the magnitude of the estimated overall back loading, this hypothesis needed to be verified. With regard to the second aim, the characteristic back-loading patterns, and in particular, peak ground-reaction forces, were hypothesized to be different between GS and SL.

METHODS

This study was approved by the ethics committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

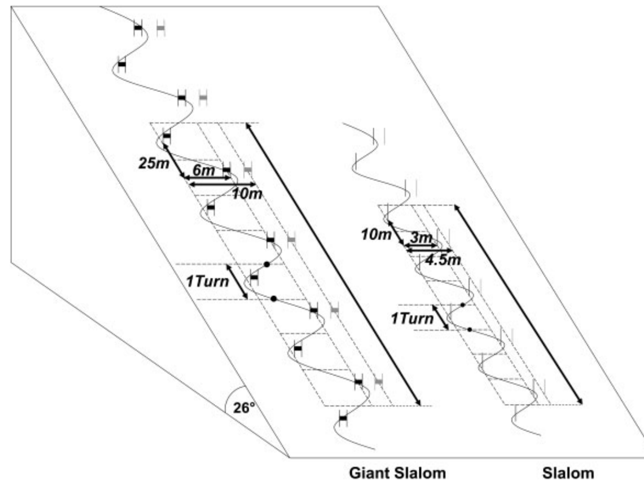

Figure 1. Schematic overview of the on-hill measurement setup.

Measurement Protocol and Data Collection

Ten athletes at the World Cup or European Cup level, all of whom had no previous history of recurrent or chronic back pain, participated in the current study. They were divided into 2 groups based on whether GS or SL was their better competition discipline in the world ranking list. The athletes of both groups performed 3 runs at 2 different course settings within their assigned competition disciplines on a 26° inclined, water-prepared icy slope (Figure 1). Within the analyzed 8-gate section, the GS course had linear gate distances of 25 m and gate offsets of 6 m (GS 25/6-m course). The alternative GS course was set with more extensive gate offsets of 10 m (GS 25/10-m course). The SL course had linear gate distances of 10 m and typical gate offsets of 3 m (SL 10/3-m course). The alternative SL course was set with more extensive gate offsets of 4.5 m (SL 10/4.5-m course). These courses were set by an experienced national team coach and aimed to represent both extremes of the gate offset distance spectrum (maximum and minimum), typical for similar conditions in World Cup Alpine ski racing. In total, 240 GS turns and 240 SL turns were considered for data analysis. The skiers' overall trunk movements were measured based on 2 inertial measurement units (Physilog; Gait Up; 500 Hz) that were fixed on the sacrum and sternum using a custom-made, skin-tight underwear suit. Ground-reaction forces were recorded by pressure insoles (PEDAR; Novel; 100 Hz). The 2 measurement systems were electronically synchronized by the use of an external trigger connected to both systems.

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Parameter Calculation and Postprocessing

The 3-dimensional (3D) orientations of the sacrum and sternum inertial measurement units were calculated using a 3D angular velocity– and acceleration-based skiing-specific algorithm. Compared with a video-based 3D kinematic reference system, this algorithm has been found to calculate the skier's trunk segment orientation with an accuracy and precision of –3.1° and 2.3°, respectively (Fasel et al, unpublished data, 2015). Next, the anatomical 3D trunk movement components (frontal bending angle, lateral bending angle, and torsion angle) were calculated. They were defined as the relative orientation between the sacrum and sternum inertial measurement units using the standard joint convention by Grood and Suntay,[9] which was anatomically adjusted to be applicable to the trunk, as was done in earlier studies.[12,18,33] Moreover, its numerical implementation was designed to be stable even at high magnitudes of lateral bending and torsion, as they are characteristic for movements in the trunk. Total ground-reaction force was defined as the sum of the force acting on both the left and the right foot and was calculated based on the signals of the 198 capacitive sensors of the pressure insoles used (PEDAR; Novel). This method has been found to systematically underestimate the absolute ground-reaction force during the outside ski phase while skiing in steep terrain by 0.23 to 0.40 N/body weight (BW), depending on the skiing situation.[25]

All kinematic and kinetic data were low-pass filtered using a second-order Butterworth filter with a cutoff frequency of 6 Hz, cut into single turn cycles and, subsequently, time normalized, as done in an earlier study.[33] The cutoff frequency was defined based on the assumption that the skiers' physiological regulation abilities are limited to a maximal frequency of approximately 6 Hz.[4,23] The beginning and end of each turn were automatically detected based on characteristic features in the total ground-reaction force curve occurring at the turn switch. Turn cycle structure was defined according to Spörri et al[34] and Reid[29] (Figure 2). In these studies, the *COM Direction Change II* turn phase was found to last from 51% to 84% of the turn cycle in GS[34] and from 53% to 77% of the turn cycle in SL.[29] Turn duration was determined as the time it took to travel between 2 adjacent turn switches. Parameter calculation and postprocessing were performed using MATLAB R2012b (MathWorks).

Statistical Analysis

The following steps of statistical analysis were performed: For each subject and their assigned discipline, 2 representative average curves were calculated (1 per course setting). Based on these individual average curves, corresponding group average curves were computed. The group average curves of the GS 25/6-m course and the SL 10/3-m course were graphically visualized as average ± SD. To compare the 2 different course settings within the competition disciplines of GS and SL, the variables' averages and maximum values were reported for the back-loading relevant turn phase *COM Direction Change II*, in which the greatest magnitudes of variables related to spinal disc loading were found to occur.[33] Subsequently, the differences between the course settings were tested by paired-sample t tests ($P < .05$), and effect sizes (Cohen d) were calculated. To compare the competition disciplines GS and SL, a similar procedure was applied. However, in contrast to the comparison between the different course settings, the differences between GS and SL (ie, between GS 25/6-m and SL 10/3-m courses) were tested by independent-sample t tests ($P < .05$), as the groups consisted of different athletes.

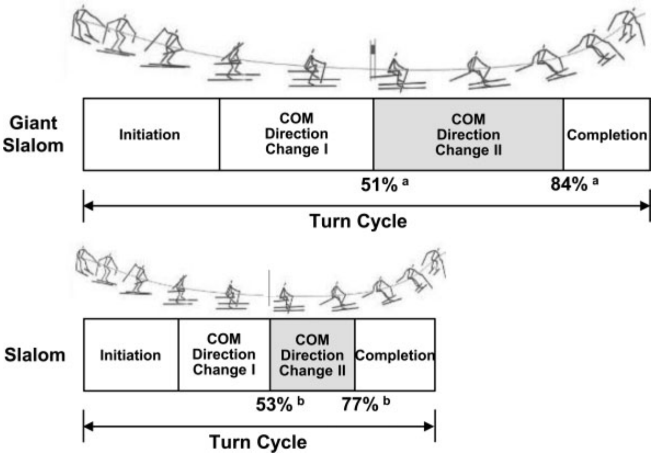

Figure 2. Turn phase definitions: [a]values according to the Spörri et al[34] study of giant slalom courses; [b]values according to the Reid[29] study of slalom courses. COM, center of mass.

RESULTS

Differences Between Analyzed Course Settings

The statistics comparing the different GS course settings with respect to the selected biomechanical variables during the back-loading relevant turn phase *COM Direction Change II* are presented in Table 1. No significant differences were found at $P < .05$ between the GS 25/6-m and GS 25/10-m courses.

In contrast, the statistics comparing the different SL course settings indicated that increasing the gate offset from 3 to 4.5 m simultaneously decreased the specific turn phase averages and maxima of total ground-reaction force by more than 10% (Table 2).

Differences Between Competition Disciplines

The group average curves illustrating the differences in the biomechanical variables related to spinal disc loading between the competition disciplines GS and SL (ie, between GS 25/6-m and SL 10/3-m courses) are presented in Figure 3 and Table 3.

Generally, similar characteristics in the variables' progressions along the turn cycle were observed. Average turn duration significantly differed between GS and SL at $P < .001$ (GS, 1.45 ± 0.11 s; SL, 0.90 ± 0.04 s). During the

TABLE 1
Selected Parameters Related to Spinal Disc Loading
for 2 Different Course Settings in Giant Slalom[a]

	GS 25/6-m Course	GS 25/10-m Course	*P* Value[c]	Effect Size (Cohen *d*)
Specific turn phase average[b]				
Frontal bending angle, deg	27.2 ± 8.3	26.8 ± 6.8	.819	0.109
Lateral bending angle, deg	11.1 ± 4.3	11.7 ± 3.5	.281	–0.557
Torsion angle, deg	6.1 ± 3.1	6.2 ± 3.6	.918	–0.049
Total ground-reaction force, N/BW	1.68 ± 0.32	1.65 ± 0.23	.645	0.222
Specific turn phase maximum[b]				
Frontal bending angle, deg	29.0 ± 8.9	28.7 ± 6.8	.858	0.085
Lateral bending angle, deg	13.7 ± 6.2	13.1 ± 4.0	.618	0.241
Torsion angle, deg	7.7 ± 3.1	8.9 ± 3.2	.166	–0.756
Total ground-reaction force, N/BW	1.81 ± 0.33	1.80 ± 0.24	.895	0.063

[a]Values are expressed as average ± SD unless otherwise indicated. Linear gate distance on course was 25 m, gate offset by 6 and 10 m. BW, body weight; GS, giant slalom.

[b]Measured during the turn phase from gate passage until the last point where center of mass markedly changes its direction (*COM Direction Change II*).

[c]There were no significant differences at $P < .05$.

TABLE 2
Selected Parameters Related to Spinal Disc Loading
for 2 Different Course Settings in Slalom[a]

	SL 10/3-m Course	SL 10/4.5-m Course	*P* Value	Effect Size (Cohen *d*)
Specific turn phase average[b]				
Frontal bending angle, deg	10.6 ± 8.4	11.4 ± 10.3	.766	–0.143
Lateral bending angle, deg	5.9 ± 2.5	7.3 ± 2.8	.312	–0.517
Torsion angle, deg	5.1 ± 1.8	5.8 ± 4.1	.569	–0.277
Total ground-reaction force, N/BW	2.13 ± 0.37	1.91 ± 0.35	.001[c]	3.502
Specific turn phase maximum[b]				
Frontal bending angle, deg	12.7 ± 9.0	13.0 ± 10.8	.939	–0.036
Lateral bending angle, deg	8.7 ± 2.0	10.1 ± 2.9	.297	–0.536
Torsion angle, deg	6.6 ± 2.7	7.5 ± 4.2	.361	–0.461
Total ground- reaction force, N/BW	2.25 ± 0.36	2.02 ± 0.39	.003[d]	2.803

[a]Values are expressed as average ± SD unless otherwise indicated. Linear gate distance on course was 10 m, gate offset 3 and 4.5 m. BW, body weight; SL, slalom.

[b]Measured during the turn phase from gate passage until the last point where center of mass markedly changes its direction (*COM Direction Change II*).

[c]$P < .001$.

[d]$P < .01$.

back-loading relevant turn phase *COM Direction Change II*, the back-loading patterns in both GS and SL included a combination of frontal bending, lateral bending, and torsion in the loaded trunk. During the same phase, GS was characterized by significantly greater average angles for frontal bending and lateral bending than were observed for SL, while SL was characterized by a trend toward greater total ground-reaction forces than were observed for GS (Table 3, top). In both disciplines, comparable magnitudes of torsion angle were observed. Similar differences were noticed for the specific turn phase maxima (Table 3, bottom).

DISCUSSION

The main findings of this study were as follows:

1. In GS, variations in course setting showed no effect on the biomechanical variables related to spinal disc loading.
2. In SL, the specific turn phase average and maximum values of total ground-reaction force during the back-loading relevant turn phase *COM Direction Change II* were found to be significantly lower when increasing the gate offset.
3. During the same phase, the back-loading patterns in both GS and SL included a combination of frontal bending, lateral bending, and torsion in the loaded trunk.
4. SL was characterized by shorter turns, lower frontal and lateral bending angles after gate passage, and a trend toward greater total ground-reaction force peaks compared with GS.

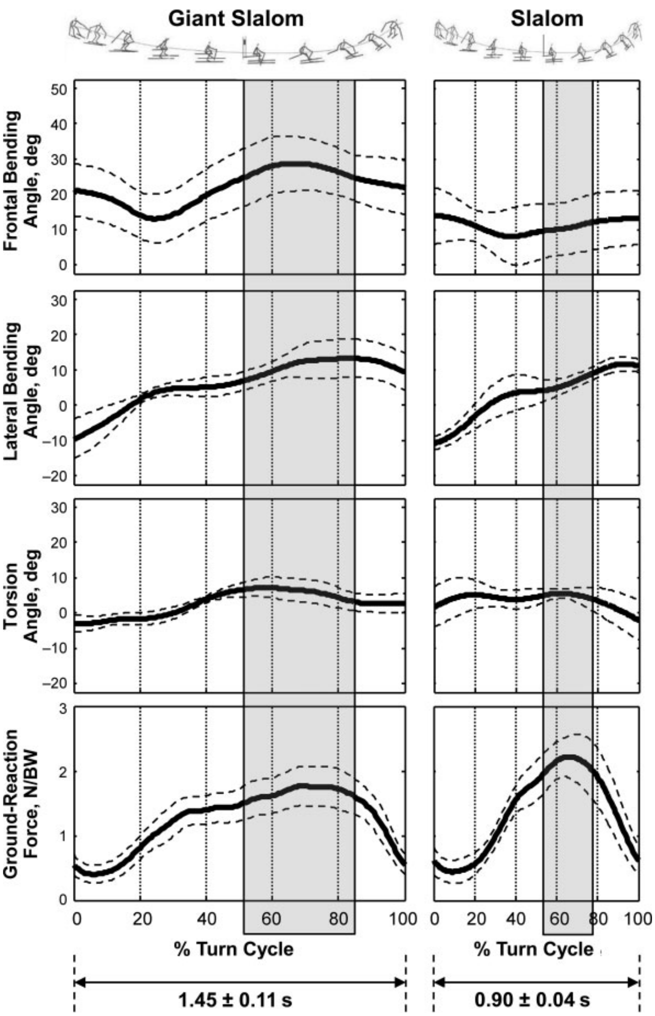

Figure 3. Overview of the discipline-specific loading patterns of the back in giant slalom (GS) and slalom (SL). The biomechanical variables related to spinal disc loading are visualized as the turn cycle normalized group average ± SD curves for the GS 25/6-m course and the SL 10/3-m course. The gray-shaded area represents the *COM Direction Change II* turn phase of each course. For a more realistic visual comparison between GS and SL, 100% of the corresponding turn cycles are plotted in proportion to the occurring average turn durations (GS, 1.45 ± 0.11 s; SL, 0.90 ± 0.04 s).

Course Setting as a Prevention Measure for Overuse Injuries of the Back

First and foremost, course setting is known as a measure that affects the mechanics of turning (eg, turn speed and turn radius), and as such, affects the acting forces.[7,34] Knowing that a combination of frontal bending, lateral bending, and torsion in the trunk coupled with high peak loads is most likely a key mechanism leading to overuse injuries of the back in Alpine ski racing,[33] an altered overall loading situation at identical trunk angles is plausible to influence the risk for overuse injuries. As illustrated in the current study, in SL, increased gate offset significantly reduced the acting ground-reaction peak forces during the back-loading relevant turn phase *COM Direction Change II*, while there was no difference in the trunk kinematics. Based on this finding, it is reasonable to conclude that in SL, increased gate offset might be an effective prevention measure for overuse injuries of the back. To reduce the magnitude of the overall back-loading, in SL and particularly steep terrain comparable to that of the current study, minimal gate offsets should be avoided. However, it has to be pointed out that these suggestions must be verified by epidemiological studies before the effectiveness of course setting as a prevention measure can be judged as conclusive.

Another interesting finding in this context is that in contrast to SL, course setting in GS seemed to have no effect on the biomechanical variables related to spinal disc loading. This might be explained by the earlier described high "quasi static loads" that typically act over a wide percentage of the turn.[16] As a consequence of these inherent loading characteristics in GS and the resulting low dynamic movement patterns of the athletes, even extreme alterations in course setting might not be able to force them to ski in a more dynamic mode. Accordingly, the 3D trunk kinematics and the skiers' loadings also would remain unchanged. This is in line with an earlier investigation that found that increased gate offset in GS resulted in loading forces that acted over a longer duration rather than in increased peak turn forces.[34]

Competition Discipline and Potential Mechanisms Leading to Overuse Injuries of the Back in Alpine Ski Racing

In Alpine ski racing, the typical loading patterns of the back are known to include a combination of frontal bending, lateral bending, and torsion in the loaded trunk.[33] As further revealed by the current study, these adverse loading patterns are an inherent part of both GS and SL turns. Since there is evidence that they increase the acting spinal torques and, as a consequence, the spinal disc loading/risk for spine deterioration,[2,10,24,30,36] it is reasonable to consider them to be important components of mechanisms leading to overuse injuries of the back in Alpine ski racing.[33] In view of this, the observed differences in the variables related to spinal disc loading between GS and SL can be considered an indication that, depending on the competition discipline, the components of the aforementioned mechanism might contribute differently to the development of overuse injuries of the back. Accordingly, different prevention measures also might be needed to effectively prevent overuse injuries of the back in GS and SL. Based on the findings of the current study, prevention measures in GS might need to control and/or reduce the magnitude of frontal bending and lateral bending in the loaded trunk. Potential prevention measures to achieve this might be superior core stability or the use of lumbar corsets. In SL, a mitigation of the short and high total ground-reaction force peaks after gate passage might need to be targeted. For that purpose, avoiding minimal gate offsets might be an effective tool, as illustrated in the current study. Additional prevention tools could be found in measures that directly affect the ski-snow interaction, such as equipment characteristics or snow preparation techniques.

TABLE 3
Selected Parameters Related to Spinal Disc Loading for Giant Slalom and Slalom[a]

	Giant Slalom	Slalom	*P* Value	Effect Size (Cohen *d*)
Specific turn phase average[b]				
Frontal bending angle, deg	27.2 ± 8.3	10.6 ± 8.4	.014[c]	1.987
Lateral bending angle, deg	11.1 ± 4.3	5.9 ± 2.5	.049[c]	1.464
Torsion angle, deg	6.1 ± 3.1	5.1 ± 1.8	.571	0.373
Total ground-reaction force, N/BW	1.68 ± 0.32	2.13 ± 0.37	.073	–1.305
Specific turn phase maximum[b]				
Frontal bending angle, deg	29.0 ± 8.9	12.7 ± 9.0	.021[c]	1.817
Lateral bending angle, deg	13.7 ± 6.2	8.7 ± 2.0	.119	1.103
Torsion angle, deg	7.7 ± 3.1	6.6 ± 2.7	.560	0.385
Total ground- reaction force, N/BW	1.81 ± 0.33	2.25 ± 0.36	.081	–1.261

[a]Values are expressed as average ± SD unless otherwise indicated. Giant slalom: linear gate distance on course was 25 m, gate offset 6 m. Slalom: linear gate distance on course was 10 m, gate offset 3 m. BW, body weight.

[b]Measured during the turn phase from gate passage until the last point where center of mass markedly changes its direction (*COM Direction Change II*).

[c]$P < .05$.

The lower frontal bending and lateral bending angles during *COM Direction Change II* in SL compared with GS might be explained by the differences in the gate clearance techniques used. In SL, pivotable single-pole gates allow the athletes to clear the gate with minimum disturbance and in a more upright and less sideward bent position, whereas in GS, double-pole gates with panels force the athletes to pass with sufficient space and in a more tucked and sideward bent position.

The trend toward greater total ground-reaction force peaks in SL compared with GS might be explained by differences in turn radii between the disciplines: In SL, the shorter gate distances and the smaller sidecut radius of the skis are plausible to result in smaller turn radii and, based on the laws of physics, smaller turn radii mean higher radial components of ground-reaction force (ie, centripetal forces), as long as the influence of the simultaneous decrease in turn speed is not predominant.

Comparing the magnitudes of the selected biomechanical variables found in the current study for GS to those reported in an earlier investigation,[33] it is obvious that the measured magnitudes of frontal bending angle and ground-reaction force were remarkably lower. This might be explained by the substantially steeper terrain and, therefore, the tighter course set in the current study. On one hand, it is reasonable that in the steep, more technical terrain, the athletes ski in a less tucked position, which might have resulted in less forward bending. On the other hand, the tighter course set in this study might have resulted in lower speed and, consequently, smaller ground-reaction forces. Thus, it can be speculated that in addition to the competition discipline and course setting, the terrain could have an effect on the biomechanical variables related to spinal disc loading. However, this hypothesis still needs to be verified, even though earlier studies have illustrated direct relationships between steeper terrain and lower speed as one factor contributing to ground-reaction force.[7]

Methodological Considerations

This study has provided a deeper understanding of the effect of increased gate offset on the overall back-loading patterns in GS and SL. Moreover, it has added the valuable complementary perspective of discipline specificity to the existing body of knowledge and detected distinct characteristics for GS and SL within the same mechanism, potentially leading to overuse injuries of the back. Nevertheless, there are some limitations of which one should be aware.

First, the study sample consisted of only 10 subjects, divided into 2 groups of 5 (GS and SL intervention groups). Each of them skied 3 runs including an 8-turn analyzed section at 2 different course settings. The resulting 24 turns per subject and course setting can be considered an appropriate data sample for providing representative subject/course average curves. Nevertheless, when comparing course settings or competition disciplines, some of the differences were observed merely as a trend even though large effect sizes were found. This might be explained by the limited number of subjects. However, it has to be pointed out that measuring valid biomechanical data on a ski track is substantially limited by the changing snow surface (when performing several runs on the same track) and by the time slot in which similar external conditions exist. This study, which was based on 480 analyzed turns, represents one of the largest data sets published in the area of Alpine ski racing research. Thus, the design of the current field study can be considered to be the best possible compromise of increasing sample size while maintaining a sufficiently high validity of the outcome measures.

Second, due to organizational and logistic restrictions of the complex in-field experimental measurement, the GS and SL groups consisted of different athletes, and only 1 specific slope inclination and snow preparation type (steep slope with water-prepared, icy snow conditions) was investigated. This might additionally limit the generalizability of the findings, particularly when comparing the competition disciplines.

Third, measuring the overall trunk motion based on 2 inertial sensors fixed to the sacrum and sternum is only a rough estimation of the underlying kinematics of the spine. It does not provide information about the 3D spinal motion at certain compartment levels, and the measured angles might slightly differ from those of the bony structures. Nevertheless, with awareness of the limited understanding of the mechanisms leading to overuse injuries of the back in Alpine ski racing and in consideration of the challenges of measuring valid biomechanical data on a ski track, the methodology used might help to provide deeper insights that are essential for the purpose of injury prevention.

CONCLUSION

This biomechanical field study found that alterations in course setting (ie, increased gate offset) reduced the occurring ground-reaction forces in SL, while in GS, neither differences in the skier's overall trunk kinematics nor differences in the occurring ground-reaction forces were observed. Thus, to reduce the magnitude of the overall back loading in SL, minimal gate offsets should be avoided.

Furthermore, this study illustrated that during the turn phase in which the highest spinal disc loading is expected to occur, the back-loading patterns in both GS and SL included a combination of frontal bending, lateral bending, and torsion in the loaded trunk. SL was characterized by shorter turns, lower frontal and lateral bending angles after gate passage, and a trend toward greater total ground-reaction force peaks compared with GS. These findings should be taken into account when defining discipline-specific prevention measures for overuse injuries of the back.

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