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Asymmetries in the Technique and Ground Reaction Forces of Elite Alpine Skiers Influence Their Slalom Performance

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Abstract: Background: Although many of the movements of skiers are asymmetric, little is presently known about how such asymmetry influences performance. Here, our aim was to examine whether asymmetries in technique and the ground reaction forces associated with left and right turns influence the asymmetries in the performance of elite slalom skiers. Methods: As nine elite skiers completed a 20-gate slalom course, their three-dimensional full-body kinematics and ground reaction forces (GRF) were monitored with a global navigation satellite and inertial motion capture systems, in combination with pressure insoles. For multivariable regression models, 26 predictor skiing techniques and GRF variables and 8 predicted skiing performance variables were assessed, all of them determining asymmetries in terms of symmetry and Jaccard indices. Results: Asymmetries in instantaneous and sectional performance were found to have the largest predictor coefficients associated with asymmetries in shank angle and hip flexion of the outside leg. Asymmetry for turn radius had the largest predictor coefficients associated with asymmetries in shank angle and GRF on the entire outside foot. Conclusions: Although slalom skiers were found to move their bodies in a quite symmetrical fashion, asymmetry in their skiing technique and GRF influenced variables related to asymmetries in performance.

Keywords: biomechanics; kinematics; kinetics; global navigation satellite system; GPS; IMU; inertial motion capture; pressure insoles; ski racing

1. Introduction

In connection with highly competitive elite alpine skiing, differences in finishing time are often very small [1]. Indeed, the overall finishing time is a major factor in determining a skier's FIS (International Ski Federation) ranking and it is therefore hardly surprising that analysis of gate-to-gate times has focused on determining where a skier loses or gains time in as much detail as possible [2,3]. However, although easy for coaches and athletes to understand [4], times on short sections of a course, such as from gate-to-gate, are not good direct indicators of either instantaneous or turning performance [5]. In this context, variables related to the dissipation of mechanical energy reflect kinetic performance more closely [5–7] and kinematic parameters related to the trajectory of the skis are also more reliable [8,9].

Although numerous descriptions of alpine skiing technique have been published, relatively little is yet known about the biomechanical factors that influence competitive performance [6]. One such factor is the start strategy, including the technique utilized and number of start-pushes [10]. Furthermore, the slalom skiing technique chosen exerts an impact on both ground reaction forces (GRF) and performance [11–13].

Thus, in the case of slalom, the larger the "attack angle" (i.e., the angle between the orientation of the skis and direction of skiing) when entering a turn, the more energy is dissipated [14], whereas with giant slalom, the choice of trajectory and smoothness of skiing during a turn are also major influences on energy loss and performance [7–9]. Furthermore, use of a more "dynamic" body posture reduces energy loss due to aerodynamic drag [15], although this is not a major determinant of the performance of elite giant slalom skiers [16]. Air drag is more important in super-G skiing and even more so when skiing downhill [17]. When skiing straight, the movement of the center of mass forwards and backwards does not affect skiing time, whereas the edge angle does [18].

Although the body movements of athletes, and especially those of left and right turns by elite alpine skiers, are often asymmetric, little is presently known about how these asymmetries influence performance [19]. Bell [20] and Hoffman [21] and co-workers have shown that asymmetries affect jump height, while Beck and colleagues [22] found that asymmetries in stride while running result in more consumption of energy. Although ski coaches are often concerned with eliminating such asymmetries (i.e., correcting "mistakes" made when performing the "worse" turn), to our knowledge, with respect to alpine skiing, only preferential usage of one of the legs is known to affect turning and the potential impact of asymmetry on overall performance remains to be determined [23].

Accordingly, our aim here was to examine whether asymmetries in technique and in the ground reaction forces associated with left and right turns influence the competitive performance of elite slalom skiers. Our hypothesis was that asymmetries in the performance of elite slalom skiers are influenced by asymmetries in their technique and in ground reaction forces.

2. Materials and Methods

2.1. Participants

Nine male slalom skiers, all members of the Swedish National Ski Team (age: 22.7 ± 3.4 y; height: 181.8 ± 6.9 cm; weight: 82.2 ± 5.6 kg; current SL FIS points: 24.9 ± 18.6 (means ± SD)), provided their written informed consent before participating in this study, which was conducted in accordance with the Declaration of Helsinki and pre-approved by the National Medical Ethics Committee (Approval ID: 0120-99/2018/5, Project ID: L5-1845).

2.2. Experimental Setup

Starting twice from the left and twice from the right side, in randomized order, each skier performed four runs on a corridor-shaped slalom course with 20 gates placed symmetrically at 12-m intervals and with a displacement of 4 m (Figure 1). To ensure that this course was set precisely, the gates were positioned using the Leica Geodetic Global Satellite Navigation System (GNSS) 1200 with its built-in Stake-Out application (Leica Geosystems AG, Heerbrugg, Switzerland). The terrain selected had an average incline of 16°, with a maximal tilt to either side of <1°, and was groomed on each day of testing. In light of the hard, icy snow and temperatures between −2 and 0 °C, the coaches and experimental team smoothed the course prior to each and every run in an attempt to standardize conditions for side-skidding.

As described previously [24,25], three-dimensional whole-body kinematics were monitored utilizing the MVN Biomech V2018 inertial system (Xsens Technologies B.V., Enschede, The Netherlands) and Leica Zeno GG04 plus Real-Time Kinematics RTK GNSS (Leica Geosystems AG, Heerbrugg, Switzerland). The inertial system (calibrated twice prior to each run) was worn under the skier's racing suit and the smart antenna (RTK GNSS) was integrated into the back protector and positioned at shoulder height to allow unobstructed satellite reception (Figure 2). Data collected by the inertial system were recorded on a memory card, while data from the GNSS RTK system were transmitted wirelessly to a handheld device (Conker NS6, Conker, Takeley, England). In connection with each measurement, the precise position of the smart antenna relative to the thoracic (T12) and cervical vertebrae (C7) was determined to allow reliable integration of these two sets of data.

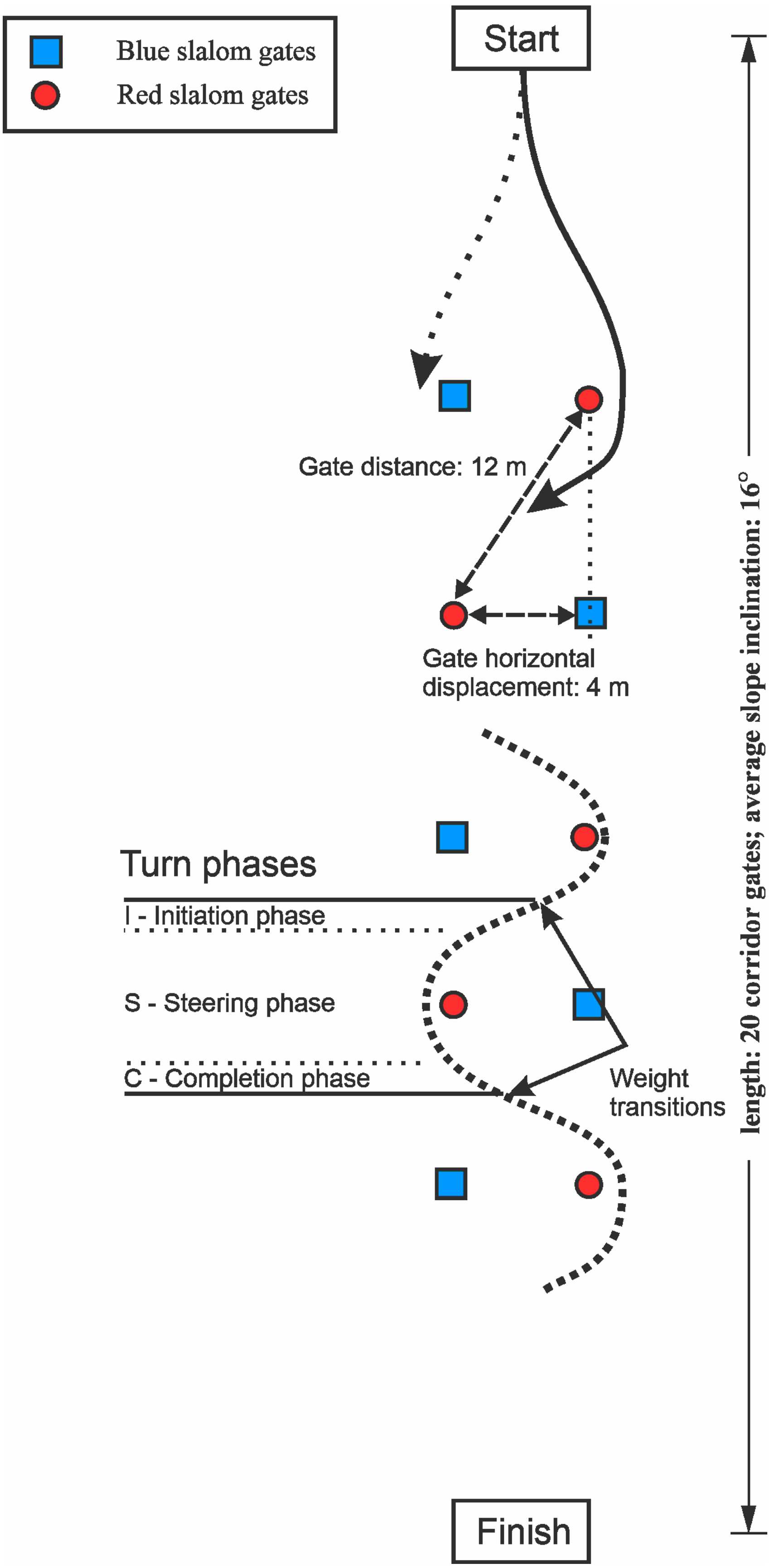

Figure 1. Schematic illustration of the corridor-shaped slalom course.

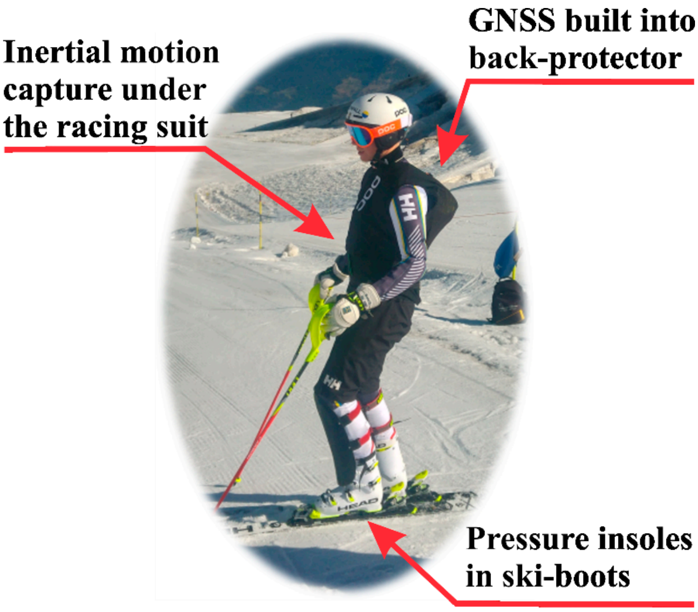

Figure 2. Equipment of the slalom skier with the global navigation satellite and inertial motion capture systems and pressure insoles.

In addition, the skier's boots were equipped with pressure insoles (Loadsol, Novel GmbH, Munich, Germany) that assessed the total ground reaction force acting perpendicular to the sole of the ski boot, the individual forces acting on the entire inside and outside foot and the distribution of force between the fore and rear foot. To assist analysis, all runs were also filmed at 50 Hz with a high-resolution camera (GC-PX100, The Japan Victor Company Ltd., Yokohama, Japan). To allow synchronization of all measurements, each skier performed three active squats and three hits with one of his skis on the ground before each start.

2.3. Computation

To match the frequency of the inertial system, the RTK GNSS system's captured trajectories at 20 Hz and the force measurements at 100 Hz were interpolated with cubic splines to 240 Hz. Following synchronization of the data collected by these three systems, these data were smoothed with the Rauch–Tung–Striebel algorithm [26], which utilizes a zero-lag two-way Kalman filter, in a manner similar to an earlier study [24]. The local coordinates provided by the inertial system were thereafter transformed into the global coordinates employed for RTK GNSS measurements by adding an extra node to the position of the RTK GNSS smart antenna. The data were subsequently transferred from Matlab R2016b (Mathworks, Natick, MA, USA) to the Visual 3D v6 software (C-Motion, Germantown, MD, USA), where the skier's center of mass (CoM) and the trajectory of the skis were calculated. The CoM was calculated utilizing Demster's regression equations [27], with inclusion of the mass of both the skiing and measuring equipment. The trajectory of the skis was defined as the arithmetic mean of the trajectories of the ankle joints [11].

The distance travelled and turn radius [7] were determined from the trajectory of the skis. From the trajectory of the CoM, the differential specific mechanical energy (i.e., the change in mechanical energy per unit change in altitude, normalized to the mass of the skier) [7] and mechanical energy for each specific section (normalized to the entrance speed) [5], which reflect instantaneous and sectional performance, respectively, were calculated. The definitions of both of these performance parameters mean that their values are negative when energy is dissipated. The flexion angles of the knee and hip joints on the left and right legs were provided directly by the inertial system. The angles of the inside and outside shanks, defined as the minimal tilt of the shank around the axis defined by the ski in relationship to the surface of the slope (Figure 3), were also calculated. Each turn was divided into initiation, steering and completion phases, as described previously [11] (Figure 1). To examine for temporal asymmetries, the left and right turning times were compared.

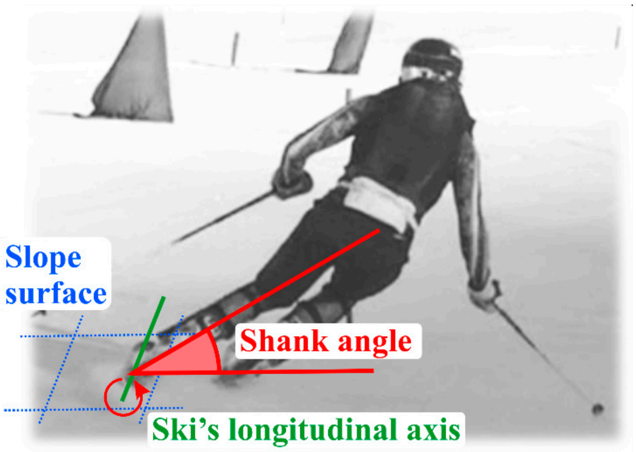

Figure 3. Photograph of a skier illustrating the angle of the shank.

Asymmetry between the left (L) and right (R) sides was expressed as the index SI = 1 − (|L − R|)/(L + R), where L and D represent the average values of parameters during the steering phase of the turn, with the exceptions of turn length, time, speed and sectional energy loss, which were determined for the entire turn. As an indicator of overall (as opposed to average) asymmetries throughout the entire turn, the Jaccard index (JI) [28] was also calculated. To obtain this index, the mean value and standard deviation of each parameter at each % of the turn were calculated. Then, the two curves obtained by adding or subtracting the standard deviation to the mean value were taken to represent the upper and lower boundaries, respectively, of the polygon delineating the turn. Thereafter, the overall JI was calculated as (A∩B)/(A∪B), where A and B represent the polygons associated with the left and right turns, respectively. In practice, when JI is equal to 1, the areas defined by the mean ± standard deviation boundaries for the left and right turns overlap entirely, whereas when JI is equal to zero, there is no overlap at all.

2.4. Statistical Analyses

All data are presented as mean values and standard deviations. The Shapiro–Wilk test was used to assess normality. Outliers detected employing standard Tukey's fences (1.5 interquartile range) were excluded from further analysis. A paired sample t-test was used for post hoc analysis of potential differences. In connection with the multivariable linear regression models, no more than two predictive (independent) variables were allowed. The dependent (predicted) variables were based on the objectives of the study related to performance (SI for turn time, turn length and average speed, and SI and JI for energy losses), while the independent (predictor) variables were related to skiing technique (SI and JI for the angles of flexion and inclination) and load (SI and JI for ground reaction forces). In connection with the multivariable linear regression models, no more than two predictive (independent) variables related to skiing technique (SI and JI for the angles of flexion and inclination) and load (SI and JI for ground reaction forces) were allowed, while the dependent (predicted) variables were related to performance (SI for turn time, turn length and average speed, and SI and JI for energy losses). All predictions in which G * Power (Faul et al., 2009, Heinrich University Heine Düsseldorf, Germany) was less than 0.8 were excluded. The level of statistical significance was set at $p < 0.05$. All statistical analyses were performed in the Matlab software.

3. Results

3.1. Descriptive Statistics, Symmetry and Jaccard Indices (SI and JI)

The descriptive statistics and symmetry indices for the independent variables (skiing technique and ground reaction forces) and dependent variables (skiing performance) during skiing are presented in Tables 1 and 2, respectively. In most cases, the differences in the independent variables during left and right turns were statistically insignificant (Table 1), the exception being GRF on the entire inside foot ($p < 0.05$). The mean symmetry indices (SI) for the independent variables related to skiing technique ranged from approximately 92 to 98%, with associated Jaccard indices (JI) during the steering phase ranging from approximately 29 to 53%. The corresponding values for the independent variables related to GRF ranged from approximately 85 to 98% and approximately 42 to 71%, respectively.

Table 1. The inclination, flexion of the joints and ground reaction forces (GRF) acting on various parts of the legs during the steering phase of left and right turns by elite slalom skiers, together with the corresponding symmetry (SI) and Jaccard (JI) indices (independent variables). All values presented are means ± standard deviations.

Variable	Left Turn	Right Turn	p-Value	SI [%]	JI [%]
Shank angle [°]					
Outside leg	30.8 ± 4.5	29.4 ± 4.6	0.49	93.8 ± 5.4	52.2 ± 19.5
Inside leg	33.2 ± 3.8	34.2 ± 2.4	0.84	92.8 ± 4.0	41.5 ± 16.2
Knee flexion [°]					
Outside leg	46.99 ± 8.9	52.20 ± 7.2	0.11	92.5 ± 4.4	28.7 ± 24.3
Inside leg	85.73 ± 9.3	81.25 ± 9.9	0.34	96.1 ± 2.2	39.1 ± 21.7
Hip flexion [°]					
Outside leg	37.4 ± 3.3	28.02 ± 3.0	0.70	95.71 ± 2.2	53.35 ± 14.9
Inside leg	71.8 ± 4.4	68.79 ± 5.5	0.22	97.52 ± 1.7	50.64 ± 15.5
GRF (pressure insoles) [% BW]					
On the entire foot					
Outside leg	126.2 ± 19.2	113.6 ± 21.6	0.21	92.9 ± 4.7	56.1 ± 18.9
Inside leg	66.8 ± 7.4	76.0 ± 10.0	0.04	91.4 ± 5.7	56.0 ± 19.6
On the fore foot [% BW]					
Outside leg	62.5 ± 20.6	58.7 ± 26.85	0.75	88.4 ± 8.4	47.2 ± 21.6
Inside leg	27.4 ± 9.2	37.8 ± 17.6	0.14	85.1 ± 10.1	42.7 ± 23.2
On the rear foot [% BW]					
Outside leg	63.8 ± 7.7	54.9 ± 16.6	0.17	87.8 ± 7.3	51.6 ± 14.4
Inside leg	39.4 ± 9.13	38.6 ± 15.8	0.85	85.8 ± 15.2	52.9 ± 23.2
GRF *					
Overall [% BW]	287.5 ± 26.3	283.7 ± 17.5	0.72	98.2 ± 1.1	71.3 ± 2.7

BW—body weight; SI—symmetry index; JI—Jaccard index; * approximated on the basis of the movement of the center of mass.

Moreover, none of the values for the dependent variables reflecting skiing performance differed significantly between the left and the right turns (Table 2). The mean SI for the dependent variables ranged from approximately 71% (in the case of instantaneous performance) to approximately 100% (average velocity). The nature of the parameters involved allowed the JI values to be calculated only for the turning radius and instantaneous performance during the steering phase as approximately 56% and 47%, respectively.

The patterns of the angle of the outside shank of all nine skiers during left and right turns, together with the corresponding JI during the steering phase (ranging from 14% for Skier I to 87% for Skier G), are shown in Figure 4. As depicted in the diagram, the mean angle of the outside shank during left and right turns differed during the entire steering phase for Skiers H and I, during the second half of the steering phase for Skiers B, D and E and during the first half of this phase in the case of Skier A. In contrast, the mean angle of the outside shank of Skier G was largely the same throughout the entire steering phase. With respect to the mean turning radius of left and right turns, most of the skiers demonstrated visible differences during the second half of the steering phase, with Skier G again being the exception (Figure 5). Moreover, the JI of 81% for the turning radius of Skier G was the largest observed, while the smallest JI of 56% in this regard was demonstrated by Skier C. Visually larger differences were observed between left and right turn instantaneous performance (Figure 6) with the JI ranging from 31% (Skier I) to 78% (Skier G).

Table 2. The time, trajectory, velocity and energy dissipation during left and right turns by elite slalom skiers, together with the corresponding symmetry (SI) and Jaccard indices (JI) (dependent variables). All values presented are means ± standard deviations.

Dependent Variable	Left Turn	Right Turn	*p*-Value	SI [%]	JI [%]
Time					
Turning time [s]	0.87 ± 0.03	0.87 ± 0.03	0.68	97.5 ± 1.7	*n*/a
Trajectory					
Turning length [m]	12.61 ± 0.30	12.51 ± 0.39	0.59	97.9 ± 1.5	*n*/a
Turningradius[m]	9.34 ± 0.44	9.32 ± 0.52	0.95	97.6 ± 1.5	56.1 ± 18.9
Velocity					
Average velocity [m/s]	14.5 ± 0.42	14.5 ± 0.37	0.97	99.6 ± 0.00	*n*/a
Energy associated with					
Instantaneous performance [J/kg/m]	−10.69 ± 4.67	−10.51 ± 2.98	0.92	70.6 ± 23.0	47.3 ± 14.1
Sectional performance [Js/kg/m]	−1.90 ± 0.39	−1.87 ± 0.50	0.91	84.2 ± 13.7	*n*/a

n/a—not applicable; SI—symmetry index; JI—Jaccard index.

3.2. Multivariable Regression Models

Altogether, our multivariable linear regression models, each involving no more than two predictor (independent) variables, included a total of 26 predictor and 8 predicted (dependent) variables. Models were discarded if the p-value was >0.05, $R^2 < 0.7$ or when the model's predictor coefficients did not differ significantly from 0 (t-statistic, $p < 0.05$). In addition, to restrict our analysis to results that could be meaningful, only the 13 models for which at least one of the predictor coefficient values was >0.1 are shown in Table 3. Of these, all included two independent variables, with the exception of Model #10, which only included one.

The largest predictor coefficients were associated with the SI values for instantaneous (differential specific mechanical energy) and sectional performance (mechanical energy for each specific section/turn normalized to the entrance speed) (Models #10–13, Table 3). The independent variables in Models #10 and 12 were related only to skiing technique, while those in Models #11 and 13 were related to skiing technique in combination with GRF. The remainder of the models had smaller predictive coefficients of 0.46 (Model #5) or lower, among which the coefficients for SI and JI for turning radius were largest (Models #4 and 5). Interestingly, the largest predictive coefficients obtained with Models #6–9, designed to predict the SI for average velocity, all corresponded to the SI for overall GRF.

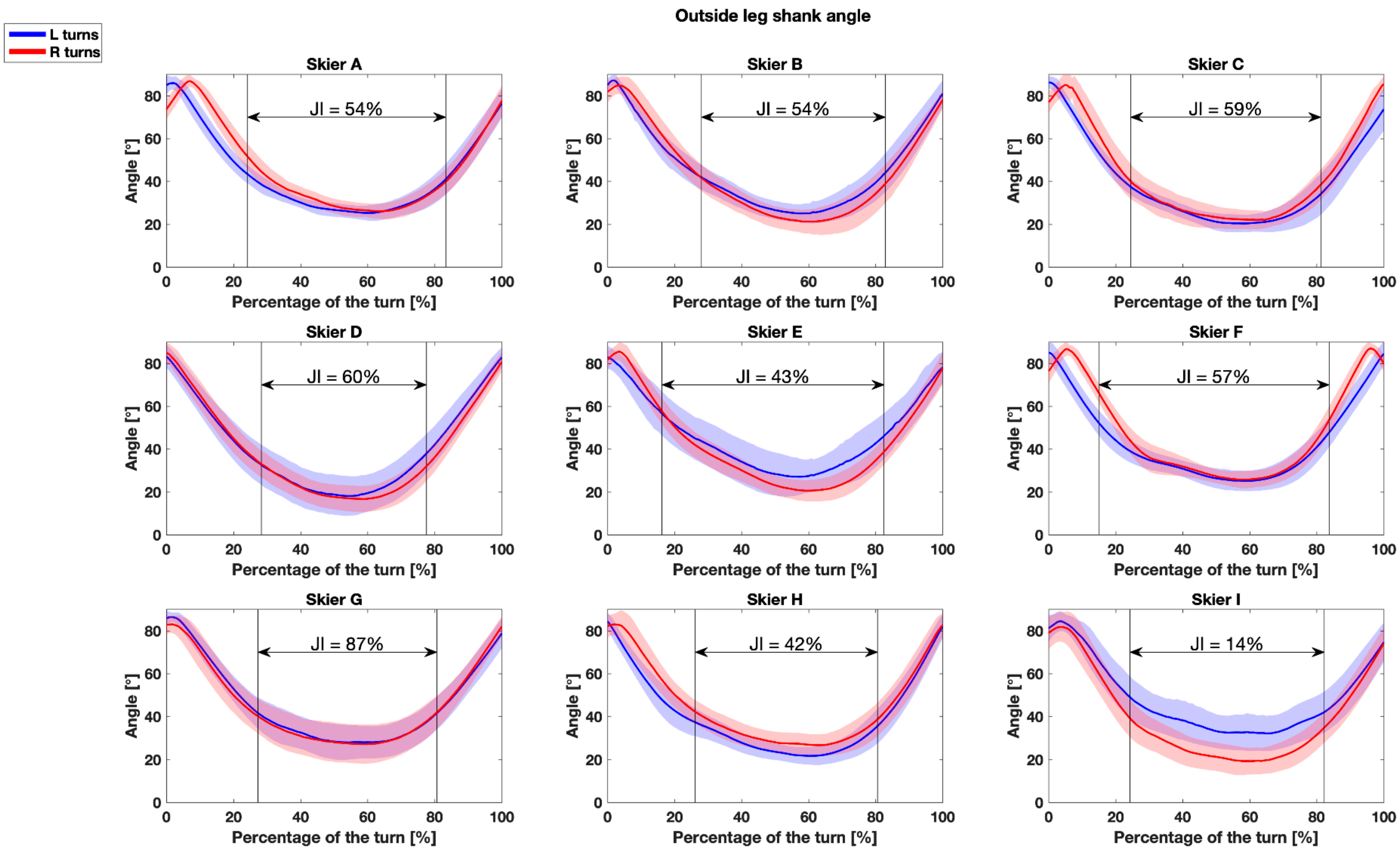

Figure 4. The angle of the outside shank of the 9 elite slalom skiers (**A**–**I**) during the steering phase of left and right turns, together with the corresponding Jaccard indices (JI). The two vertical lines indicate the beginning and end of the steering phase.

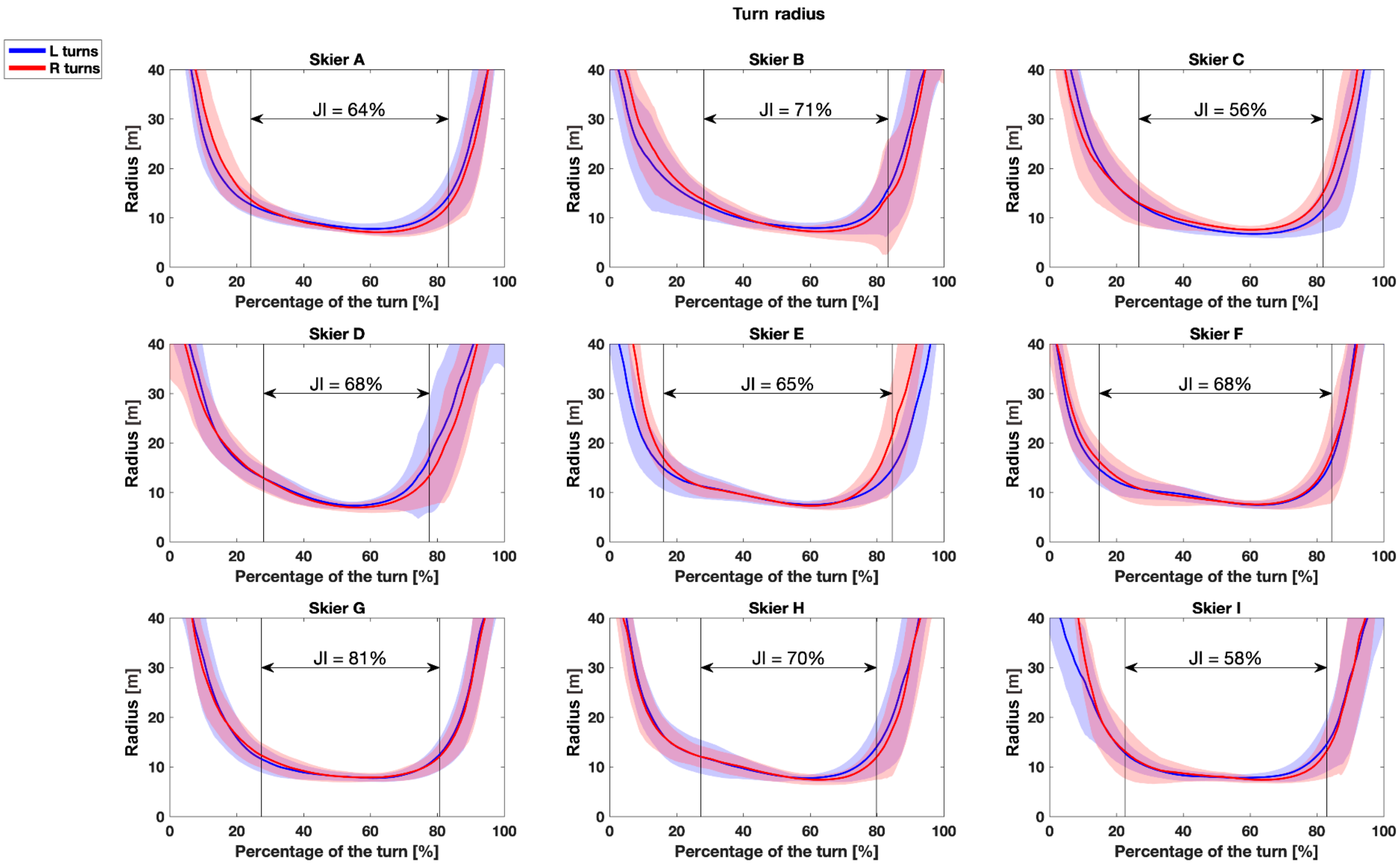

Figure 5. The turn radii during the steering phase of left and right turns by 9 elite slalom skiers (**A**–**I**) and corresponding Jaccard indices (JI). The two vertical lines indicate the beginning and end of the steering phase.

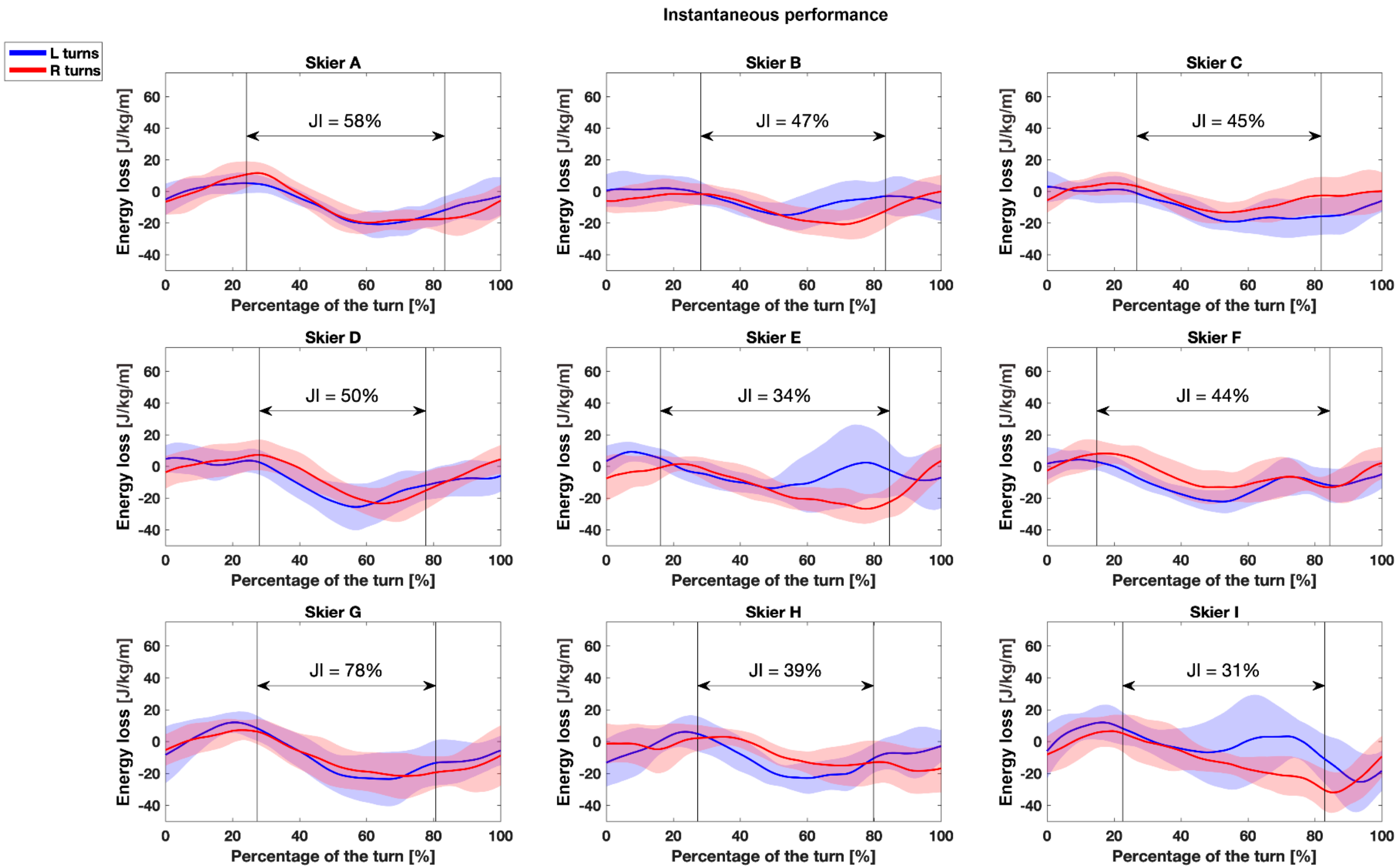

Figure 6. The instantaneous performance during the steering phase of left and right turns by 9 elite slalom skiers (**A**–**I**) and corresponding Jaccard indices (JI). The two vertical lines indicate the beginning and end of the steering phase. Instantaneous performance is defined as energy dissipation per change in altitude normalized relative to the mass of the skier and his equipment.

Table 3. Multivariable linear regression analysis of the relationships between the predicted (dependent, columns) and predictor (independent, rows) variables. The values in each column represent the coefficients of predictor variables.

Dependent Variables → Independent Variables ↓	SI for Turning Time	SI for Turning Length	JI for Turning *n* Radius	SI for Turning Radius	SI for Average Velocity	SI for Instantaneous Performance	SI for Sectional Performance
Shank angle							
JI for outside leg	-	-	0.33 **,#4	-	-	-	-
SI for outside leg	-	-	-	-	-	3.97 ***,#10	3.01 **,#13
JI for inside leg	0.08 *,#1	0.07 **,#2	-	-	-	-	-
SI for inside leg	-	-	-	-	-	5.77 **,#11, 7.16 **,#12	-
Hip flexion							
JI for outside leg	-	-	-	−0.10 *,#5	0.01 *,#6	-	-
SI for outside leg	-	-	-	-	0.09 *,#7	8.33 *,#12	-
GRF on entire foot [a]							
JI for GRF outside leg	-	-	0.25 *,#4	-	-	-	-
SI for GRF outside leg	-	-	-	0.46 **,#5	-	-	-
SI for GRF inside leg	0.14 *,#1	0.13 **,#2, 0.11 *,#3	-	-	-	-	-
JI for GRF inside leg	-	-	-	-	-	-	0.56 *,#13
GRF on rear foot [a]							
JI for outside leg	-	-	-	-	−0.02 **,#8	−1.03 **,#11	-
SI for GRF outside leg	-	-	-	-	−0.03 **,#9	-	-
Overall GRF [b]							
JI	-	0.16 *,#3	-	-	-	-	-
SI	-	-	-	-	0.10 *,#6, 0.12 **,#7, 0.15 **,#8, 0.16 **,#9	-	-
R^2	0.72 *,#1	0.80 **,#2, 0.75 *,#3	0.80 **,#4	0.74 *,#5	0.73 *,#6, 0.81 **,#7, 0.84 **,#8, 0.83 **,#9	0.86 ***,#10, 0.82 **,#11, 0.84 **,#12	0.76 **,#13

* —$p \leq 0.05$, ** —$p \leq 0.01$; *** —$p \leq 0.001$; # *n*—multivariable regression model number; GRF—ground reaction force; SI—symmetry index, JI—Jaccard index; [a] determined by pressure insoles; [b] approximated on the basis of the movements of the center of mass.

4. Discussion

The major novel finding here was confirmation of the hypothesis that asymmetries in technique and ground reaction forces are associated with asymmetries in the performance of elite, competitive slalom skiers. More specifically, (i) asymmetries in instantaneous and sectional performance were associated with the largest predictor coefficients for asymmetry in the angle of the shank and hip flexion on the outside leg; and (ii) asymmetry in turning radius demonstrated the largest predictor coefficients for asymmetry in the angle of the shank and GRF on the entire foot of the outside leg.

Our descriptive statistics showed that, on average, these elite alpine skiers performed left and right turns quite symmetrically (Tables 1 and 2), with the only statistically significant difference between these turns being the GRF on the entire foot of the inside leg. In particular, the average mean values for performance were almost identical for the left and right turns (Table 2). Furthermore, the symmetrical indices (SI) were all above 84% (sectional performance), except for instantaneous performance (70%).

This symmetry, which in light of the very small differences in performance of elite alpine skiers [9,29,30] was not unexpected, confirmed that our experimental setup was well suited for observing differences between left and right turns. Previously, the differences in the GRF and temporal parameters associated with left and right slalom turns by highly skilled ski instructors were also reported to be non-significant [23]. Similarly, the mean difference in strength between the dominant and non-dominant legs of elite Austrian alpine skiers was also small [31].

In the present case, the only SI that was markedly lower concerned instantaneous performance (70.6%). Overall, sectional and instantaneous performance demonstrated the most pronounced asymmetries, which was the initial rationale for employing these as measures of alpine skiing performance [5,7,30]. In giant slalom as well, utilization of energy-based performance over an entire section was found to be a valuable measure of performance [9].

However, the Jaccard indices (JI) revealed much more pronounced asymmetry between left and right turns, with the lowest value being only 28.6% (for flexion of the outside knee) and the highest 71.3% (for the overall GRF) (Table 1). The lowest individual JI value for the angle of the outside shank was only 14% (Skier I, Figure 4) and during the steering phase, a difference between left and right turns by this skier was clearly visible. This same skier exhibited the lowest JI for instantaneous performance (Figure 6) and the second lowest for turning radius (Figure 5). At the same time for Skier G, the largest JI for the angle of the outside shank (Figure 4) was associated with the largest JI values for both turning radius (Figure 5) and instantaneous performance (Figure 6). The dependence of sectional and instantaneous performance on the SI for the angles of both the inside and outside shank received further support from the multivariable regression analysis (Models #10–13, Table 3). Similarly, the JI for turning radius proved to be dependent on the corresponding value for the angle of the outside shank (Model #4, Table 3), an observation which in itself clearly demonstrates that asymmetry in technique is associated with asymmetry in performance. Such a relationship is not entirely unexpected, since according to the theory of carving skiing, the inclination of the ski is related to turning radius [32] and, moreover, in the case of slalom skiing, turning radius is related to instantaneous performance [5].

The SI for turning radius was not dependent on the SI for the angle of the outside shank. This independence demonstrates that the mean turn values taken into consideration when calculating SI did not take the profound turn cycle information into account as was the case with JI values in Model #4 (Table 3). The SI for turning radius was negatively correlated with the JI for flexion of the outside hip (predictor coefficient −0.10, Model #5, Table 3). This negative association means that less pronounced asymmetry in flexion of the outside hip should correspond to more asymmetry in the turning radius, an observation that we were unable to explain at present.

The predictor coefficients for JI and SI for the GRF acting on the entire foot of the outside leg were also relatively large in connection with the JI and SI for the turning radius (Models #4 and 5, Table 3). This finding can be explained by the action of radial forces, whose basic biomechanical modeling has shown to be dependent on the turning radius [32,33]. In this context, it is important to emphasize that only the GRF acting on the outside leg, not the overall GRF, was a predictor in the multivariable models. Indeed, in a previous study [5], this overall GRF did not differ between better and poorer slalom skiers. However, in the present investigation, the SI for average velocity was dependent on the corresponding value for the overall GRF in combination with several other "less important" variables with small predictor coefficients (Models #6–9, Table 3). This particularly interesting finding reveals that despite the virtually identical average velocity and overall GRF associated with left and right turns by our elite skiers, the asymmetries in these variables were actually large enough to demonstrate related dependency in the multivariable models (Tables 1 and 2).

The largest predictor coefficients observed in our multivariable models concerned the dependence of the SI for instantaneous performance on the combination of the SI values for the angle of the inside shank and flexion of the outside hip (Model #12, Table 3). The only apparent explanation for this dependency is the speculation that skiing technique influenced how smoothly the skis glide, (e.g., the attack angle defined as the angle between the longitudinal axis of the ski and the ski's center point's velocity vector projected onto a plane parallel to the surface of the snow) [14]) and/or the distribution of pressure under the ski and thereby the ski–snow interaction [34]. Either or both of these influences could exert an impact on energy dissipation.

Finally, some of the symmetry indices (SI) observed here, such as those for turning time, turn length and sectional performance, were dependent on various parameters related to the asymmetry of the inside leg (Models #1–3 and 13). This indicates that asymmetries in performance were also associated with the behavior of the inside leg, which has earlier been suggested to only play a role in maintaining stability while skiing [35]. Ski coaches already pay special attention to the inside leg in connection with training to optimize performance, but our findings provide the first experimental evidence that this is a valid concern.

Although the current investigation was extensive, assessing the full-body three-dimensional kinematics and GRF in connection with 720 slalom turns, like all studies, has certain limitations. Although some researchers question the reliability of inertial measurement systems and GNSS and/or pressure insoles, their reliability for in-field measurements on alpine skiers has already been demonstrated [23–25,35–39] and, moreover, we utilized state-of-the-art technology in this respect, i.e., one of the most up-to-date and accurate Leica Geosystems RTK GNSS systems and the latest version of the Xsens inertial motion capture hardware. However, since it was not possible to install an inertial sensor on a foot in a ski boot, we were unable to monitor flexion of the ankle joint. It would have been possible to measure bending of the ski boot, but this does not entirely reflect the more complicated three-dimensional behavior of the ankle joint (i.e., technique).

In addition, although GRF can certainly be measured most accurately with dynamometers/force-plates [40], the size and weight of these devices disturb the skiing equipment and, thereby, the performance of the skier. To avoid this, we used pressure insoles here, which do not always indicate the magnitude of GRF accurately [41]. On the other hand, direct measurement of the pressure on the soles, an important parameter when skiing [23,35], is especially useful for dealing with asymmetries in pressure on different parts of the foot. To assess a more precise magnitude of the GRF, we performed biomechanical modeling of this parameter based on the acceleration of the center of mass monitored by three-dimensional kinematics, as in our previous studies [11,42].

As is true of virtually all studies on alpine skiing, generalization of our present results, despite the relatively large size of our study population, is not straightforward. The snow, terrain and weather were nearly ideal during our testing and similar studies under varying conditions are now required.

5. Conclusions

In conclusion, the application of descriptive statistical analysis to left and right turns by elite slalom skiers revealed that with respect to technique, ground reaction forces and performance, these turns were quite symmetrical, with the only significant difference being related to the mean GRF on the entire inside foot. Furthermore, all symmetry indices for skiing technique and performance were >92%, with the exception of those for instantaneous (70.6%) and sectional performance (84.2%), demonstrating the relevance of these latter two parameters in connection with the analysis of skiing asymmetry. The Jaccard index, which takes into account behavior within the turn cycle, was found to be more sensitive to asymmetries than the symmetry index, which is based solely on the mean values of the parameters. Although the movements of elite slalom skiers were found to be quite symmetrical, this is the first demonstration that asymmetry in their skiing technique and ground reaction forces influences asymmetry in their performance. These findings constitute experimental support for the efforts of coaches to achieve symmetrical skiing technique, not only in order to decrease the risk of injury [31], but also to optimize overall performance.

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