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# Kinetic keys to alpine skiing performance: A 3-D analysis of ground reaction forces and torques

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## ABSTRACT

Alpine skiing performance hinges on the dynamic interaction between the skier and the ski-snow interface. Ground reaction forces are fundamental in controlling these interactions, yet surprisingly little research exists characterising 3-D turn kinetics. This study aimed to profile the evolution of ground reaction forces and torques signatures applied by skiers during turning and explore their link with giant slalom performance. Seventeen male alpine skiers with varying skill levels, equipped with ski-mounted force plates, executed multiple trials on a giant slalom ski course. A statistical parametric mapping approach was used to explore relationships between normal force and anteroposterior torque signatures with race times. Faster race times were correlated with greater normal force during the plateau phase of the turn crux ( $p < 0.001$ ) and lower during turn switch ( $p = 0.006$ ). Better times were also associated with higher positive ( $p = 0.004$ ) and negative ( $p < 0.001$ ) rates of force development. The best skiers appeared to apply an elevated positive  $M_y$  plateau ( $p < 0.001$ ) with a steeper slope ( $p = 0.029$ ) on the inside ski at turn initiation. Our findings indicate generating large forces and rapidly modulating their application to the skis is a crucial aspect of skiing performance.

## ARTICLE HISTORY

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## KEYWORDS

Alpine skiing; performance; kinetics; force plate; giant slalom

## 1. Introduction

In Alpine skiing, athletes control their movement by exerting forces on the snow through their boots and skis (R. C. Reid, 2010; R. C. Reid et al., 2020). The resulting ground reaction forces (GRF) are central to performance basis, with their nature, orientation, and intensity significantly influencing speed and trajectory. Understanding skiing kinetics and exploring potential ways they can be modified is interesting to both scientists and coaches.

Skiing involves responding to diverse external forces, including gravity, aerodynamic friction, ski/snow-friction, and GRF. While gravity is a constant force, its influence on a skier's movements varies depending on the characteristics of the slope. Aerodynamic drag fluctuates with the skier's velocity and position, and thus garners limited interest outside speed-dominated events, such as downhill and super-G (Gilgien et al., 2018; Supej et al., 2013). Both forces are considered consistent or predictable, and thus less meaningful to performance differences in Slalom or Giant Slalom than the forces involved in turning. The lateral snow friction force results from ski-snow interactions. This force enables the radial

component of the ground reaction force ( $F_r$ ), which relates to the turn radius and the velocity of completion (i.e.  $(\text{velocity}^2 \times \text{body mass})/\text{radius}$ ). The resulting GRF is manipulated to enable the athlete to turn back and forth down the slope, otherwise controlling their speed. Turning motion (e.g., body inclination towards the inside of the turn and in the fall line, asymmetric flexion/extension of the lower limbs, and modification of shoulder-pelvis alignment) influences the position and action of the skis on the slope (Lind & Sanders, 2004). Skiers can adjust three main parameters: downslope traversing angle relative to horizontal, ski-snow edge angle in the sagittal plane, and attack angle, which is the angle between longitudinal ski orientation and the centre of gravity's displacement vector (R. C. Reid et al., 2020). Vertical actions, such as lower-limb extension or flexion, and the anteroposterior position of the skier change the force applied on the ski and the point of application of the force, respectively (P. Federolf et al., 2008). Modulating the force applied normally to the ski ( $F_z$ ) is usually considered a critical parameter of skiing kinetics (Supej & Holmberg, 2019). Although it receives less

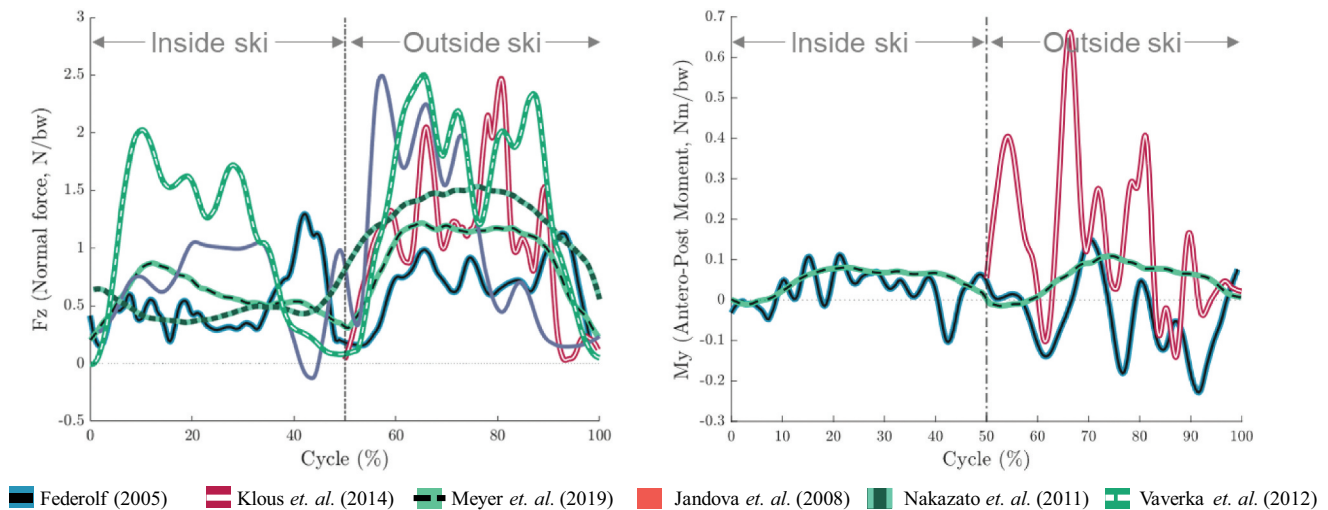
attention, anteroposterior torque ( $M_y$ ) seems to be linked with skier behaviour and turning technique (Thorwartl et al., 2023). In our opinion,  $M_y$  kinematics could provide insight into the mechanism of skis bending at turn initiation and the location of the point of force application along the ski during the turn. Since GRF is linked with motion and kinematics (i.e., speed and turn radius), it follows that specific events likely characterise turn phases. Thus, measuring the intensity and timing of 3-D GRF facilitates a better understanding of factors underlying performance in alpine ski racing (Matej Supej & Holmberg, 2019).

Collecting quality GRF data during skiing requires specifically designed force platforms integrated with the skis and bindings (Nakazato et al., 2011). Such units provide several advantages over the more common insole technology, namely a more thorough representation of force in 3-D (e.g., including otherwise 'missed' force applied to the cuff of the boot). The technology needs to function in demanding settings, introducing various practical challenges. This not only renders experimental sessions more complex, often leading to extended setups, but also potentially inhibits skiers from performing their best. Notably the weight of the setup and heightened bindings can result in compromised skiing movements during descent. Recently, several lighter and more compact force platforms have been developed and validated; nevertheless, only six recent studies have presented force or torque data on one or more axes (P. A. Federolf, 2005; Jandova & Vaverka, 2008; Klous et al., 2014; Meyer et al., 2019; Vaverka & Vodickova, 2010). Unfortunately, although Nakazato et al., study included the most skiers, level groups, and analysed turns, their study did not focus on understanding kinetics during alpine skiing and was more focused on comparison between measurement system technologies rather than understanding kinetics during alpine skiing. Other studies feature few subjects and limited turns. More factors complicating synthesis which are: different slope gate settings (i.e., two studies focus on slalom (SL) (Jandova & Vaverka, 2008; Vaverka et al., 2012), three on giant slalom (GS) turns (P. A. Federolf, 2005; Klous et al., 2014; Meyer et al., 2019), and variable slope settings), and the treatment applied to the data (e.g., some report individual data without filtering or smoothing (P. A. Federolf, 2005; Klous et al., 2014), others present smoothed and group-averaged data (Meyer et al., 2019; Nakazato et al., 2011)). Figure 1 presents data from six previous studies to aid in qualitative kinetics characterisation of a ski turn. Despite different methodologies, turn kinetics exhibit similar overall temporal patterns ('force signature'): for both feet,  $F_z$  is close to zero at turn switch, tends to increase to a plateau for

some studies (Meyer et al., 2019; Nakazato et al., 2011) or at least a period of elevated force peaks with respect to the overall turn, and then decreases. The  $F_z$  peaks were higher on the outside ski than on the inside ski. While synchronised data are rare, these events seem to align with the timing event previously reported for: the turn phases (notably those proposed by Supej (Supej et al., 2015)), the changes in the knee angle (Alhammoud et al., 2020), and the evolution of ski edge angles (R. C. Reid et al., 2020). Unfortunately, the sparse data on torques are inconclusive, and challenging to synthesise due to drastic differences in intensities, timing, and direction.

Rendering a consensus on the association between force signatures and performance is further complicated by the innate difficulty of quantifying skiing performance during a given turn (P. A. Federolf, 2012). For example, there is evidence that lower-level slalom skiers produce greater peak GRF, negatively correlated with acceleration, and dissipate more energy per unit of altitude (Supej et al., 2011). The authors of this finding explained that higher GRFs probably correspond with phases of strong friction (e.g., skidding or mistakes), so short *radii* and strong frictional forces should be avoided to maximise slalom performance. In contrast, consistently greater maximum (outside and inside ski) and average (inside ski, only) force values was observed among experts than intermediate skiers during the driving phase across various course settings and steepness (Nakazato et al., 2011). These contradictory correlations between GRF and performance are not mutually exclusive and likely reflect findings derived from distinct situations: higher  $F_z$  can result from increased radial forces during faster skiing or sharper turns, achievable by applying greater average force to the ski; alternatively, it might arise from an external peak force on the skis caused by excessive friction, either from skidding or errors. Ultimately, the delineation between force applied to turn the skis and that due to otherwise unnecessary braking confounds interpretation. In any case, based on simple physics and according to radial force definition skiing faster with a consistent turn radius requires the athlete to apply greater radial force oriented towards the inside of the turn (Cross et al., 2021), until which point they reach their muscular or the ski/snow interaction limit (Chollet et al., 2024).

The supposed positive association between  $F_z$  and performance can be explained in several ways. Firstly, more loading on the outside ski (increasing  $F_z$ ) flexes it into the snow and reduces turn *radii* (similarly, increasing  $F_z$ ). This also acts to increase the radial friction of the ski via increasing snow penetration and normal forces (P. Federolf et al., 2006), allowing the skis to stay 'on edge'



**Figure 1.** Graphic representation of the vertical force and moment on the y-axis in previous research. The figures represent the evolution of normal force ( $F_z$ , in N/bw) and moment in the y-axis ( $M_y$ , in Nm/bw) during a turn cycle (as % of total), for the left and right panels, respectively. Data from the inside and outside skis are indicated on each panel. Each colour corresponds to the results presented from each of the six different studies.

and enabling higher  $F_z$  and turn speeds. Thus, the technical level of the skier and his capacity to flex the outside ski and maintain good ski snow interaction (carving) (R. C. Reid et al., 2020) is ultimately associated with increases in  $F_z$  and ski deformation (Thorwartl et al., 2023). Secondly, during turn switch, expert skiers present higher minimum force and average force than intermediate skiers (Nakazato et al., 2011). Since interacting with the ski/snow is the primary means of a skier changing trajectory, one explanation is that higher-level athletes maintain more consistent contact with the snow to ensure control. Another explanation is that higher-level athletes execute turn-switch movements within reduced timeframes (Delhaye et al., 2020), which may result in increased force and torque during the turn transition phase to provide an equal quantity of energy to the snow in a shorter time. Exploration of force and torque production along other axes in skiing remains sparse. To gain a comprehensive understanding of the dynamics of skiing, it is essential to consider torque alongside force data interpretation. If forces are indeed correlated with performance, analysing the accompanying moments can offer additional insight. Nevertheless, at present there is no consensus on either the association between force signature and skier performance, nor a more detailed exploration of specific kinetic events during turning.

Therefore, the aims of this study were to 1) describe the changes in 3-D kinetics in the ski-snow interface within the entire turn (force-signature) over a large population of skiers, and 2) characterise associations between individual force-signature and skiers' performance. For the latter aim, we hypothesised that higher-performing skiers would ski faster and exhibit a

greater  $F_z$  plateau. Accordingly, since higher amount of force (i.e., impulse) should be produced in shorter time, the rate of force ascent and descent (i.e., the increasing and decreasing parts of the curve) would be greater for better skiers. Secondly, we hypothesised that  $F_z$  and  $M_y$  intensities during the initiation phase of the turn will be also positively correlated with skiers' performance.

## 2. Material and methods

### 2.1. Participants

Seventeen male alpine skiers (mean  $\pm$  SD: age  $28.6 \pm 9.3$  years, height  $179.7 \pm 5.7$  cm, weight  $75.6 \pm 9.3$  kg) performed several trials of a giant-slam course. The skiers were selected to represent a spectrum of performance levels and included good recreational skiers (not ranked by the International Ski Federation [FIS]) to top-ranked current and previous World Cup competitors (FIS points  $< 2$ ). Each skier was informed of risks and benefits of the study and gave their written consent to participate, with the procedures congruent with the Declaration of Helsinki and approved by the local ethics committee of the Université Savoie Mont-Blanc.

### 2.2. Experimental protocol and data collection

The experiments took place on a non-water-injected moderate-grade slope ( $\sim 25^\circ$ ), set in GS style by a former national ski coach. The course comprised 16 gates spaced at an average horizontal distance of  $\sim 23$  m and an offset of  $\sim 8$  m. The testing lasted five weeks, during

which the gate placements were measured (via multi-point triangulation) and reset.

All data collection occurred between 9:00 a.m. and 12:00 p.m., only when the temperature the previous night was cold enough to freeze the snow. Snow quality (hardness, humidity < 60 %, temperature ~ 1 °C) and environmental conditions (temperature, wind, visibility) were consistently observed, and testing was postponed if these values were unacceptable until they stabilised (or delayed until the following day). Due to warmer late-morning conditions towards the end of the data collection window, salt was sometimes used to maintain a consistent hard snow surface.

During experimentation, skiers performed 2 to 4 familiarisation runs of the slope while equipped with the various technologies. These descents allowed for warm-up and habituation to the race route and the measurement equipment. The skiers then followed a protocol for calibrating and zeroing the force platforms pre-run, and performed one or two race-paced runs separated by ~15 minutes passive recovery (including the chairlift ascent and re-calibration). Skiers were asked to ski as fast as possible while avoiding risk of falling and reported whether they achieved this successfully post-run. Race time was measured with a FIS-approved laser cell system (Tag-Heuer – La Chaux-de-Fonds – Switzerland), and the trial with the fastest time was used for further analysis.

### 2.3. Skis and boots

Athletes wore standardised race skis (SALOMON Lab X-Race – Anncy – France; *radius*: 30 m, length: 1.93 m) and appropriately sized ski boots (SALOMON XLAB 140+ WC – Anncy – France). This removed variability from differing ski/boot setups and ensured a predictable interface between the force plates, boots, and bindings. Athletes used their own race suits and other FIS approved race clothing and protective equipment (e.g., helmet, goggles, back protectors).

### 2.4. Force plates

Skiers were equipped with a custom set of onboard validated force plates (Falda-Buscaiot et al., 2016), that were bolted to the boots and integrated with standard bindings. The sensors (Sensix – Poitiers – France) weighed 1400 g per foot and raised the skier by 6 mm. The force plates comprised two sensors per ski, placed at the front and rear of the boot, each with six strain gauges. A specific calibration matrix was used for each boot size and according to the pair of skis used during the experiment. During each trial, ground reaction forces

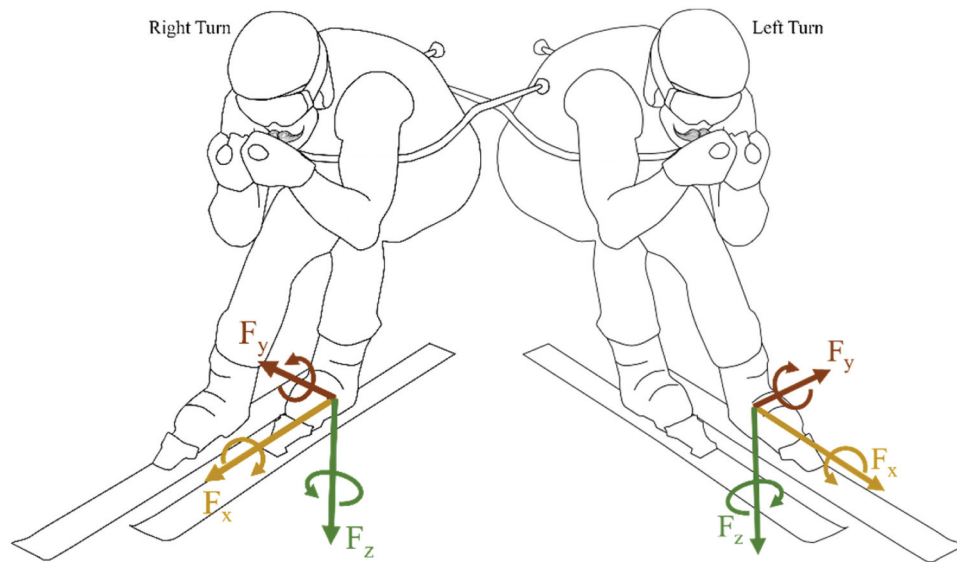
and torques were amplified and recorded at 200 Hz by hardwiring an acquisition unit worn in a hip bag (~1 kg, including battery). The reference frame for the force plates is shown in Figure 2.

### 2.5. Data analysis

While data from both left and right skis were collected, only that from the left was used for analysis due to issues with damaged wiring partway through collection. Data from each run were normalised to body weight (bw) and low-pass filtered (3 Hz Butterworth). Using the minimum force between the skis to determine turn initiation (Nakazato et al., 2011), each trial was separated into cycles comprising two consecutive turns: 1) measured ski inside and 2) measured ski outside of the turn. Turns were temporally normalised to compose seven cycles comprising inside and outside turns (seven of each) used for further analysis. Subsequently, the filtered and normalised force and torques of all race cycles were averaged for each skier. Subsequently, these temporally homogenous  $F_z$  and  $M_y$  data were used for time-series representations. Time derivatives were computed to characterise the change in force and torque (e.g., the rate of force development/relaxation at turn initiation/completion) and evaluate patterns in our subsequent analyses. To provide descriptive data, balance between force produced on the inside and outside ski was calculated as the ratio between mean  $F_z$  of the plateau during the steering phase. To aid in interpretation, kinematic events as 'points' (in % of cycle) were extracted from the existing literature (i.e., digitalised and averaged from Figure 4 of Spörri et al., 2012) and overlaid onto the corresponding data. In the article by Spörri, turn phases were determined based on the radius of skier centre of gravity (CG) passing above/below a 30 m threshold. Phases are considered identically on both inside and outside turns: turn initiation between points  $f - a$  and  $c - d$ , steering phase between points  $a - b$ , and  $d - e$  and completion between points  $b - c$  and  $e - f$ . While these indexes were based on kinematic events and slalom, we believe they provide a sufficiently robust point of reference for the purposes aiding in the interpretation of turn dynamics. Points  $c$  and  $f$  correspond to the previously described turn switch events. In their raw form, these data were used to address our first aim of providing an in-depth descriptive analysis of ski turns.

### 2.6. Statistical analysis

Statistical analysis was performed using Matlab. Specifically, the statistical parametric mapping (Analysis is performed with SPM) was performed using the Matlab



**Figure 2.** Representation of the orthonormal frame reference kinetic data measured from the boot-mounted force plates. Orthonormal frame reference for right and left turns. Note that because  $F_z$  was normal to the surface of the ski, it is positive when directed towards the ground. A positive torque on the  $M_x$  axis generates rotation of the cuff of the ski boot inside the turn. The torque on the  $M_y$  axis generates anteroposterior rotation and is positive when the skier leans forward and negative when the skier leans backward.

toolbox `spm1d` (version M.0.4.6–2019.08.22) published by Todd Pataky.

Descriptive statistics for the various turn events were calculated for primary kinetic data and aided in addressing our first aim. To address our second aim, the mean force and torque signals of each skier (normalised turn duration) and their associated derivatives were correlated with race time using SPM (Pataky, 2010). Briefly, SPM divides the data into small units called nodes and calculates statistical values for each node to identify patterns or relationships between variables in the data. However, to avoid the risk of false positives arising from many iterations of statistical processes, SPM adopts Random Field Theory to identify clusters of significant nodes that are unlikely to be due to chance (i.e., supra-threshold clusters). This approach is useful for analysing continuous data, such as the kinetics over normalised turn duration in this study, and avoids reducing the data dimension related to lost information. Two main analyses were completed, with performance (i.e., race time) being the target variable, and corresponding kinetic data expressed over the turn duration (%): 1)  $F_z$  and  $M_y$ , to evaluate the main interaction between skier motion and ski/snow interaction; and 2) Time derivative of  $F_z$  and  $M_y$ , to evaluate the slope of the force signature. Magnitude of associations was evaluated using SPM correlation with specific Pearson correlation coefficients ( $r$ ) with a significant threshold of  $p < 0.005$ , to adjust for inflated type I error. Correlations were interpreted using thresholds of

$r < 0.1$ , 0.3, and 0.5, for trivial, small, and moderate magnitudes, respectively.

### 3. Results

The mean race time is equal to 29.45 s ( $\pm 1.88$  s). The values of  $F_z$  and  $M_y$  at specific timings identify by Spörri et al. (2012) specific timing are detailed in Table 1. The balance of force between inside/outside ski is equal to 41/59% at the begin of steering phase (point “a” and “d”) and 36/64% at the end of steering phase (point “b” and “e”). To illustrate the differences in force application between high- and low-performing skiers, Figure 3(c) shows the average force-time signatures of the two fastest (in red, mean race time: 26.90 s) and the two slowest (in green, mean race time: 32.72 s) participants. The mean repartition during all steering phases was 27/73% for the inside/outside ski, respectively. Figures 3 and 4 display the key findings and relationships between kinetic signature ( $F_z$  and  $M_y$ ), and race-time (supplementary material presents other axes  $F_y$ ,  $M_x$ , and  $M_z$ ).

$F_z$  was correlated with race time in three zones. Specifically, there was a negative association with race time (i.e., greater  $F_z$ , better performance) between 11.1% and 39.4%, and 60.0% and 89.3% of turn durations (all  $p < 0.001$ ). Positive associations with race time (i.e., greater  $F_z$ , worse performance) were observed between 47.2 and 52.0% ( $p = 0.011$ ). The derivative of  $F_z$  was negatively associated with race time between 38.8 and 43.0% and between 89.7 and 93.0% (both  $p < 0.001$ ) of the turn cycle and

**Table 1.** Descriptive values of key force and moment data per turn phase.

Measured ski	Indices	Phase	Cycle (%)	$F_z$		$M_y$	
				N	bw	Nm	bw.m
Inside	a	Initiation	<b>0–11.5</b>	<b>277</b>	<b>0.37</b>	36	0.05
		Steering	<b>11.5–41</b>	<b>398</b>	<b>0.54</b>	<b>–5</b>	<b>0</b>
	b	Completion	<b>41–50</b>	<b>232</b>	<b>0.31</b>	<b>–23</b>	<b>–0.03</b>
Turn switch	c		[50]	84	0.11	14	0.02
Outside	d	Initiation	<b>50–61.5</b>	<b>386</b>	<b>0.52</b>	<b>58</b>	<b>0.08</b>
		Steering	<b>61.5–91</b>	<b>1059</b>	<b>1.42</b>	<b>23</b>	<b>0.03</b>
	e	Completion	<b>91–100</b>	<b>302</b>	<b>0.40</b>	<b>–30</b>	<b>–0.04</b>
Turn switch	f		[100]	29	0.04	–8	–0.01

Measured ski represents the position of the measured ski in referential of the turn. Indices represent events that delineate turn phases (i.e., ‘Phase’), with Points a, b, d, e extracted from existing literature (Spörri et al., 2012) and applied to our dataset. Points c and f correspond to the point of minimal normal force (i.e. turn-switch); Cycle (%) represents the point or area at which the event occurred or been average and displayed as a percentage of total turn cycle. with the corresponding kinetic values at indices or mean during phase:  $F_z$ , normal force expressed in N, Newtons and bw, bodyweight;  $M_y$ , moment in y-axis expressed in Nm, Newton-meters.

positively associated with 57.2 and 59.5% ( $p = 0.004$ ) of the cycle (see Figure Suppl. 7 Digital Supplementary Materials).

$M_y$  values were correlated with race time values at the beginning of the cycle between 3.9 and 10.8% of the cycle time ( $p = 0.005$ ). In this case, higher torques were associated with lower time and better performance. Similarly,  $M_y$  derivative from 2.1% to 3.1% ( $p = 0.029$ ) was negatively associated with race time.

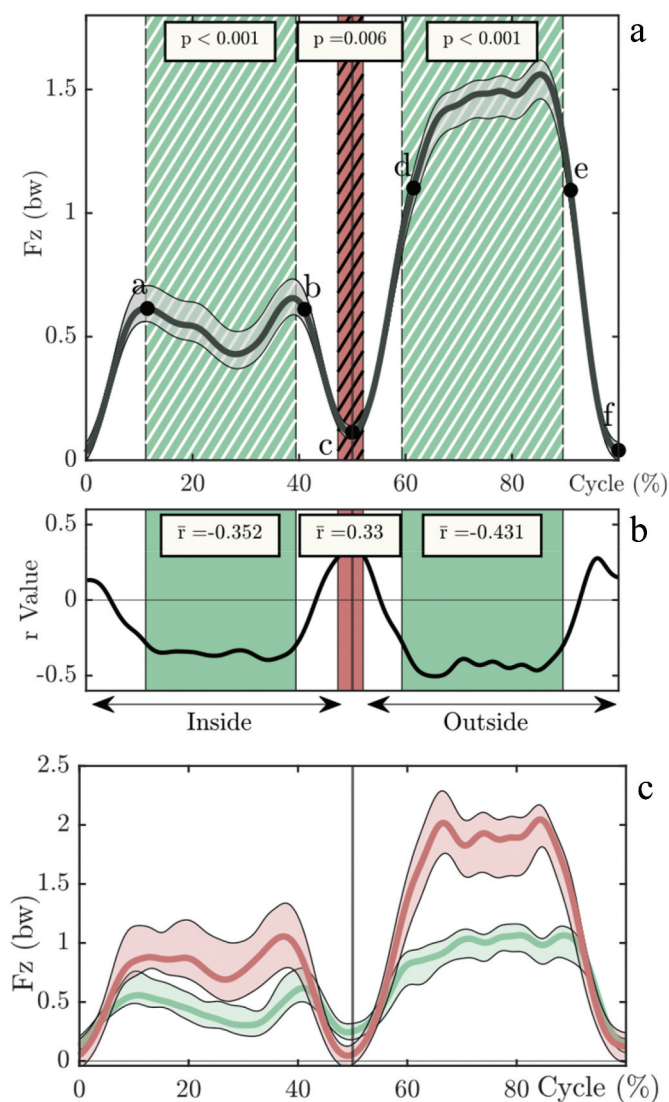
#### 4. Discussion

In this study, our overarching objective was to gain a deeper understanding of three-dimensional kinetics in skiing and explore its association with performance. By analysing a substantial dataset comprising 17 skiers, 119 cycles, and 238 turns, we observed a distinct pattern in the evolution of forces and torques. Our analyses indicate that some force and torque signature patterns are associated with skier race time. During the steering phase of the turn, lower race times (i.e., better performance) seem to be linked with maximising the applied normal force on both the inside and outside skis, creating a higher force plateau with steeper ascending and descending slopes. Conversely, better skiers appeared to minimise the force during the turn switch. Furthermore, race time is negatively correlated with positive values and rate of torque development of  $M_y$  on the inside ski at turn initiation, corresponding to higher peak forward moment on the inside foot.

The measured  $F_z$  aligns with the descriptive synthesis shown in Figure 1. Force plateaus are separated by a phase of low force amplitude, which likely corresponds

to the release of ski edges and reduced pressure during the turn switch. The magnitudes of  $F_z$  during the turn phase ( $\sim 1.5bw$ ) fall within the range reported in the literature for similar turn radii (approximately 1 and 2.2 bw) (P. A. Federolf, 2005; Klous et al., 2014; Meyer et al., 2019).  $F_z$  cycles exhibit alternating high and low forces, with the characteristic plateau being higher on the outside ski compared to the inside ski (average force distribution of 27 and 73% for the inside and outside skis, respectively). Similar force distributions have been previously reported ( $\sim 1:2$  inside: outside), albeit with different technological, methodological (e.g., geomorphological characteristics), or analytical techniques (Cross et al., 2020; Meyer et al., 2019; Nakazato et al., 2011). This kinetic imbalance between the two skis is one of the bases of carving turns (LeMaster, 2009). According to previous research (Delhaye et al., 2019), the steering phase determined based on the turn radius appears to correspond with the  $F_z$  plateau and the force and torque in other axes. Moreover, these kinetic behaviours and kinematics points appear to correspond to those reported in previous studies (Supej et al., 2015) and other key parameters of skiing motricity (Alhammad et al., 2020; R. Reid et al., 2009; R. C. Reid et al., 2020).

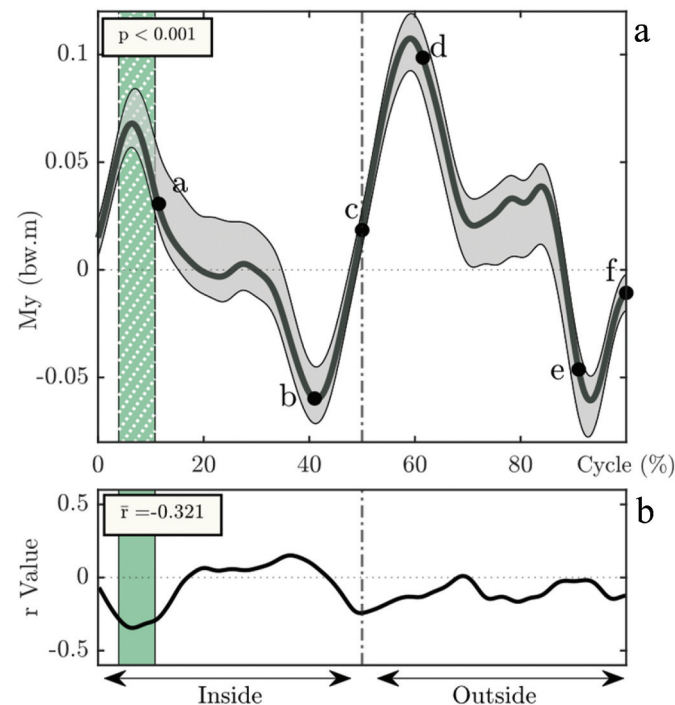
We observed a U-shaped pattern during the force plateau on the inner leg, with a dip in force during the main steering phase compared to the beginning and end of the steering phase. This pattern could be attributed to behaviour during the previous turn and turn switch: applying force at the end of previous steering phase (Brierley & Bartlett, 1991), pushing into the snow, unweighting the skis, and quasi-jumping into the next



**Figure 3.** a. Grey line represents the evolution of the mean  $F_z$  of the left ski during a cycle, respectively normalised by skier's body weight. Standard deviation is represented by the gray surface. Data include between 0 and 50 % of the cycles corresponding to left turns where ski is observed inside the turn, and 50–100 % of the following right turns where ski is observed outside the turn. Points *a*, *b*, *d*, and *e* correspond to the timing events of turn phases: initiation, steering, completion according to Spörri (2012), and points *c* and *f* correspond to the point of minimal normal force and turn-switch and correspond to the data presented in Table 1. Coloured and hatch area represents a “SPM cluster”, that is the period of the cycle when force signature is correlated with race-time. Red with black hatch areas are relative to positive correlation, green bands with a white hatch where area force data is negatively correlated with the race time. For each cluster of correlation, p-value of the test is displayed. b. The  $r$  value of the SPM(t) correlation test is presented below the force signatures. The mean  $r$  value of the cluster is display. c. Presents the mean force-time signature of the two participants with the fastest (red, mean race time: 26.90 s) and slowest (green, mean race time: 32.72 s) race times.

turn. This hypothesis seems congruent with kinematic analyses showing hip and knee extension of the inside leg and flexion of the outside leg at the end of the steering phase (Alhammoud et al., 2020). Feasibly, these movements could be related to a ‘pushing’ action of the inner leg at the end of the steering phase to lighten load – ultimately inducing lower  $F_z$  at the turn switch. Higher-level skiers may also emphasise bending the rear portion of the skis into the snow (consistent

with the observed negative My moment at the end of the turn) to store elastic energy for sudden release (Thorwartl et al., 2023) at the unweighting, which could occur simultaneously with the push on the inside leg, amplifying the force. A lower minimum value of  $F_z$  during the transition between two turns may also be a strategy to increase the rate of force development (RFD) for the following turn, as observed before a drop jump (Bobbert et al., 1987). This finding diverges from



**Figure 4.** a. Grey line represents the evolution of the mean  $M_y$  of the left ski during a cycle, respectively normalised by skier's body weight. Standard deviation is represented by the gray surface. Data include between 0 and 50 % of the cycles corresponding to left turns where ski is observed inside the turn, and 50–100 % of the following right turns where ski is observed outside the turn. Points *a*, *b*, *d*, and *e* correspond to the timing events of turn phases: initiation, steering, completion according to Spörri (2012), and points *c* and *f* correspond to the point of minimal normal force and turn-switch and correspond to the data presented in Table 1. Coloured and hatch area represents a “SPM cluster”, that is the period of the cycle when force signature is correlated with race-time. Red with black hatch areas are relative to positive correlation, green bands with a white hatch where area force data is negatively correlated with the race time. For each cluster of correlation, p-value of the test is displayed b. The  $r$  value of the SPM{t} correlation test is presented below the force signatures. The mean  $r$  value of the cluster is display

the typical pattern described in the literature (P. A. Federolf, 2005; Meyer et al., 2019; Nakazato et al., 2011) and requires further investigation.

Our analyses support the association between force production characteristics and performance measures. We observed a moderate inverse correlation between early steering phase  $F_z$  intensity for both the inside ski (12–39% cycle) and outside ski (60–98% cycle) and race time, indicating that higher forces are associated with better performance. Interestingly, the  $F_z$  intensities at the start and end of the steering phases seemed to indicate slightly stronger associations with race time compared with the middle of the plateau (Figure 3b). This tendency was also visually observable in the extremum of the population (Figure 3c) This may suggest that specific turning techniques are linked to performance outcomes. However, given that these differences fall within a relatively wide cluster that was deemed statistically significant, the small variations in association strength (e.g., on the inside ski  $r = -0.36$  (at 14% of cycle) vs.  $-0.33$  (at 28% of cycle) vs.  $-0.40$  (at 34% of the cycle) may not be practically meaningful. Further

investigation is required to determine whether these differences have practical relevance beyond statistical significance. Reports of lower turn radii at the start and end of the steering phases compared to the middle (Matej Supej, 2008) suggest that a more ‘U-shaped’  $F_z$  profile during a turn is associated with an increased radial force. Consequently, skilled skiers may possess physical and technical capabilities (Cross et al., 2020, 2021; Hydren et al., 2013) to apply larger radial forces, enabling them to achieve or maintain higher velocities while dissipating less energy.

The derivatives of  $F_z$  exhibited moderate correlations with skiers' race time at specific points in the cycle: 39% and 43% (positive correlation,  $p < 0.001$ ), 57 and 60 % (negative correlation,  $p = 0.004$ ), and between 90 and 93% of the cycle (positive correlation,  $p < 0.001$ ). This implies that even when time is normalised, better skiers demonstrate steeper rising and falling slopes of the  $F_z$  plateau. Thus, both positive and negative RFD (Maffioletti et al., 2016) muscular capabilities may be required for higher-level skiing on snow. Although alpine skiing does not involve high angular velocities

of the knees or pelvis ( $\sim 90^\circ/\text{s}$ ) (Alhammoud et al., 2020), it demands near-maximum muscle contractions in response to external inertial stressors (Turnbull et al., 2009). Taken together with findings indicating that RFD and maximal force production in isometric conditions vary with skier level (Cross et al., 2020), better GS skiers may produce more force but also attain their force plateau quicker during the steering phase.

Descriptively, the evolution of  $M_y$  (Figure 4) during turns exhibits a general curve shape characterised by high positive torque (forward movement) at the end of the initiation phase and beginning of the steering phase, followed by high negative torque (backward movement) at the end of the steering phase and beginning of the turn switch. During the steering phase,  $M_y$  torque remains close to zero for the inside ski and slightly positive for the outside ski, indicating that the skier applies a slight forward pressure to the boot cuff. The overall  $M_y$  signature aligns with Klous et al. (2014) in terms of positive values during the first third of the turn and negative values during the last third. However, the magnitude in our study was greater by a factor of 10. Conversely, our magnitudes align more closely with Meyer et al. (2019), although the  $M_y$  signatures differ notably, with a negative phase of low intensity at initiation (from 0 to 15%; 0.005 bw.m) followed by exclusively positive values in a typical form (increase, plateau, decrease). These differences may arise from variations in methodological and data analysis approaches. Nonetheless, these descriptive data will serve as a template for qualitative comparisons in future studies. At turn initiation, the positive torque indicates the forward force exerted by the skier, which is consistent with the actions detailed by Muller *et al.* (1998). This involves the skier aligning towards the fall line and leaning forward into the turn, aiming to induce flexion at the ski's front without needing edge angle or radial force (Thorwartl et al., 2023; Yoneyama, 2018). The forward movement of the skier's centre of gravity during this phase is crucial. Given our data's variance, strategies might differ based on the skier's profile or expertise, where the skier orients towards the fall line and engages the body forward and inside the turn, or potentially actively flexes the limbs to more quickly reposition them to apply force in the proceeding turn phase. According to our data, the intensity of  $M_y$  during initiation was greater on the outside ski than on the inside ski, likely because of a lower distribution of  $F_z$  to the inside foot.

The moderately positive associations between  $F_z$  and race time during the turn switch partially contradict our second hypothesis, suggesting rather that greater  $F_z$  (in this phase) is associated with worse performance. However, there was a negative association between early  $M_y$  of the inside ski (4–11% of cycle,  $p = 0.001$ )

and race time, indicating that the best skiers maximise forward loading on the inside foot during the initiation phase. These findings suggest a link between  $M_y$  and  $F_z$  intensity, with better-performing skiers reducing  $M_y$  and  $F_z$  at the turn switch and increasing  $M_y$  at turn initiation. This result is consistent with the quasi-jumping behaviour during the turn switch previously described. While not explored in this study, it is possible that the actions involved in the turn switch need to be performed in less time for faster skiers (Delhaye et al., 2020), necessitating greater lightening of  $F_z$  at turn switch and increased force and torque at turn completion and initiation.

Consistent with prior research, our findings demonstrate a clear association between  $F_z$  and skiing performance. While a momentary high  $F_z$  may be linked to energy dissipation (Supej et al., 2011),  $F_z$  also represents the ability to withstand high radial force. Managing a high radial force requires both physical capacity and technical expertise to apply it to the snow. Overall, better skiers exhibit a more 'dynamic' force signature, characterised by increased unweighting between turns, a higher loading rate on  $F_z$  during steering, and greater forward pressure ( $M_y$ ) on the inside ski. These characteristics indicate a turn transition achieved through targeted force application, where skiers quasi-jump from one turn to the next to develop the highest amount of impulse in the shortest time. This behaviour appears to be specific to high-level skiers, likely resulting from enhanced physical and technical capabilities.

This paper focused on exploring the relationship between normal and anteroposterior force signals and performance, without investigating the potential links between different force and moment components. Although this study provides valuable insights, further research could delve into these interrelationships and potentially uncover additional relevant information.

#### 4.1. Limitations

Firstly, using race time as a measure of performance is highly macroscopic and may not fully capture turn performance, as it is influenced by factors beyond the force signature. For example, a high-level skier who makes an isolated mistake that minimally affects the mean force signature may still experience a degraded race time while being considered on par with a lower-level skier who did not make such a mistake. Furthermore, the performance index used, similar to others in the literature, is influenced by environmental conditions and course settings. Despite our efforts to control for variables, variations in snow quality among skiers could introduce differences in experimental conditions. Moreover, while its impact may be

normalised across individuals, skiers' familiarity with ski gear and experimental devices could have introduced variability.

## 5. Practical applications

The findings of this study indicate that skilled skiers experience higher forces during the steering phase, which is partly due to their higher velocities and smaller turn radii, in either case reflecting their ability to handle these forces effectively. Furthermore, our results demonstrate the crucial role of timing in applying these forces and torques and provide a qualitative blueprint for turn cycle kinetics. These insights have implications for coaches, athletes, equipment manufacturers, and researchers in the field of sports medicine, providing a more nuanced understanding of the kinetic behaviours associated with enhanced skiing performance. Moving forward, researchers could explore the specific techniques and training approaches that enable skiers to optimise force application and timing, which could stimulate advancements in conditioning approaches and equipment design. Additionally, considering the influence of environmental conditions, future studies should investigate how variations in snow quality and course settings impact the force and torque characteristics during skiing. Overall, this study opens avenues for future research, contributing to ongoing efforts to enhance skiing performance and optimise training strategies.

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CD, MRC, and FH collected the data. CD, MRC, and MB analysed the data. All authors were involved in scoping the research design and interpretation. CD and MRC compiled the initial manuscript, with all authors involved in the revision and editing for final submission.

## References

- Alhammoud, M., Hansen, C., Meyer, F., Hautier, C., & Morel, B. (2020). On-field ski kinematic according to leg and discipline in elite alpine skiers. *Frontiers in Sports and Active Living*, 2 (May). <https://doi.org/10.3389/fspor.2020.00056>
- Bobbert, M. F., Huijing, P. A., & Van Ingen Schenau, G. J. (1987). Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Medicine & Science in Sports & Exercise*, 19(4), 339–346. <https://doi.org/10.1249/00005768-198708000-00004>
- Brierley, H., & Bartlett, R. M. (1991). A three-dimensional video analysis of the kinematic differences between experienced and novice skiers performing two types of parallel ski turn. *Journal of Sports Sciences*, 9(4), 393–451. <https://doi.org/10.1080/02640419108729899>
- Chollet, M., Delhaye, C., Samozino, P., Bowen, M., Morel, B., Monjo, F., & Hintzy, F. (2024). The “velocity barrier” in giant slalom skiing: An experimental proof of concept. *Scandinavian Journal of Medicine and Science in Sports*, 31 (1), 1–11. <https://doi.org/10.1111/sms.14515>
- Cross, M. R., Delhaye, C., Morin, J. B., Bowen, M., Coulmy, N., Hintzy, F., Samozino, P., & Federolf, P. A. (2021). Force output in giant-slalom skiing: A practical model of force application effectiveness. *PLOS ONE*, 16(1), 1–22. <https://doi.org/10.1371/journal.pone.0244698>
- Cross, M. R., Rivièrè, J. R., Coulmy, N., Morin, J. B., & Samozino, P. (2020, November). Lower limb force-production capacities in alpine skiing disciplines. *Scandinavian Journal of Medicine and Science in Sports*, 1–13. <https://doi.org/10.1111/sms.13897>
- Delhaye, C., Cross, M., Bowen, M., Samozino, P., & Hintzy, F. (2019). Kinetic and kinematic turn switch detection in giant slalom. In M. Karczewska-Lindinger, A. Hakkarainen, V. Linnamo, & S. Lindinger (Eds.), *Science and skiing VIII. Vuokatti sports technology Unit of the faculty of sport and health sciences* (pp. 73–79). University of Jyväskylä.
- Delhaye, C., Cross, M. R., Bowen, M., Samozino, P., & Hintzy, F. (2020). Influence of line strategy between two turns on performance in giant slalom. *Frontiers in Sports and Active Living*, 2(Nov). <https://doi.org/10.3389/fspor.2020.589257>
- Falda-Buscaiot, T., Hintzy, F., Rougier, P., Coulmy, N., & Lacouture, P. (2016). Development of a new 6-components

- force sensor design for biomechanical research in alpine skiing. In E. Müller, J. Kröll, S. Lindinger, J. Pfusterschmied, J. Spörri, & T. Stöggl (Eds.), *Science and skiing VII* (pp. 348–356). Meyer & Meyer Sport Ltd.
- Federolf, P. A. (2005). *Finite element simulation of a carving snow ski*. (Thesis). ETH Zurich. <https://doi.org/10.3929/ethz-a-010782581>
- Federolf, P. A. (2012). Quantifying instantaneous performance in alpine ski racing. *Journal of Sports Sciences*, 30(10), 1063–1068. <https://doi.org/10.1080/02640414.2012.690073>
- Federolf, P., JeanRichard, F., Fauve, M., Lüthi, A., Rhyner, H. U., & Dual, J. (2006). Deformation of snow during a carved ski turn. *Cold Regions Science and Technology*, 46(1), 69–77. <https://doi.org/10.1016/j.coldregions.2006.06.006>
- Federolf, P., Scheiber, P., Rauscher, E., Schwameder, H., Lüthi, A., Rhyner, H.-U., & Müller, E. (2008). Impact of skier actions on the gliding times in alpine skiing. *Scandinavian Journal of Medicine & Science in Sports*, 18(6), 790–797. <https://doi.org/10.1111/j.1600-0838.2007.00745.x>
- Gilgien, M., Kröll, J., Spörri, J., Crivelli, P., & Müller, E. (2018). Application of dGNSS in alpine ski racing: Basis for evaluating physical demands and safety. *Frontiers in Physiology*, 9 (Mar). <https://doi.org/10.3389/fphys.2018.00145>
- Hyden, J. R., Volek, J. S., Maresch, C. M., Comstock, B. A., & Kraemer, W. J. (2013). Review of strength and conditioning for alpine ski racing. *Strength & Conditioning Journal*, 35(1), 10–28. <https://doi.org/10.1519/SSC.0b013e31828238be>
- Jandova, S., & Vaverka, F. (2008). Ground reaction forces measurement based on strain gauges in alpine skiing. *The Impact of Technology on Sport II*, September. <https://doi.org/10.1201/9781439828427.ch119>
- Klous, M., Müller, E., & Schwameder, H. (2014). Three-dimensional lower extremity joint loading in a carved ski and snowboard turn: A pilot study. *Computational & Mathematical Methods in Medicine*, 1–13. <https://doi.org/10.1155/2014/340272>
- LeMaster, R. (2009). *Ultimate Skiing*. Human Kinetics.
- Lind, D., & Sanders, S. P. (2004). *Physics of skiing - skiing at triple point*. Springer Science. <https://doi.org/10.9781/4419-1834-5>
- Maffioletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: Physiological and methodological considerations. *European Journal of Applied Physiology*, 116(6), 1091–1116. <https://doi.org/10.1007/s00421-016-3346-6>
- Meyer, F., Prenleloup, A., & Schorderet, A. (2019). Development of a new embedded dynamometer for the measurement of forces and torques at the ski-binding interface. *Sensors (Switzerland)*, 19(19), 4324. <https://doi.org/10.3390/s19194324>
- Müller, E., Bartlett, R., Raschner, C., Schwameder, H., Benko-Bernwick, U., & Lindinger, S. (1998). Comparisons of the ski turn techniques of experienced and intermediate skiers. *Journal of Sports Sciences*, 16(6), 545–559. <https://doi.org/10.1080/026404198366515>
- Nakazato, K., Scheiber, P., & Müller, E. (2011). A comparison of ground reaction forces determined by portable force-plate and pressure-insole systems in alpine skiing. *Journal of Sports Science and Medicine*, 10(4), 754–762. <https://doi.org/10.1007/s12283-013-0119-x>
- Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics*, 43(10), 1976–1982. <https://doi.org/10.1016/j.jbiomech.2010.03.008>
- Reid, R. C. (2010). *A kinematic and kinetic study of alpine skiing technique in slalom*. (Dissertation). Brage NIH. [https://doi.org/10.1016/S0925-8388\(03\)00235-4](https://doi.org/10.1016/S0925-8388(03)00235-4)
- Reid, R. C., Haugen, P., Gilgien, M., Kipp, R. W., & Smith, G. A. (2020). Alpine ski motion characteristics in slalom. *Frontiers in Sports and Active Living*, 2(Mar), 1–11. <https://doi.org/10.3389/fspor.2020.00025>
- Reid, R., Gilgien, M., Moger, T., Tjorhom, H., Haugen, P., Kipp, R., & Smith, G. (2009). Turn characteristics and energy dissipation in slalom. In S. Lindinger, T. Stöggl, & E. Müller (Eds.), *Science and skiing IV* (pp. 419–429). Meyer & Meyer Verlag.
- Spörri, J., Kröll, J., Schiefermüller, C., Müller, E., & Schwameder, H. (2012). Course setting and selected biomechanical variables related to injury risk in alpine ski racing: An explorative case study. *British Journal of Sports Medicine*, 46(15), 1072–1077. <https://doi.org/10.1136/bjsports-2012-091425>
- Supej, M. (2008). Differential specific mechanical energy as a quality parameter in racing alpine skiing. *Journal of Applied Biomechanics*, 24(2), 121–129. <https://doi.org/10.1123/jab.24.2.121>
- Supej, M., Hébert-Losier, K., & Holmberg, H. C. (2015). Impact of the steepness of the slope on the biomechanics of world cup slalom skiers. *International Journal of Sports Physiology and Performance*, 10(3), 361–368. <https://doi.org/10.1123/ijsp.2014-0200>
- Supej, M., & Holmberg, H.-C. (2019). Recent kinematic and kinetic advances in Olympic alpine skiing: Pyeongchang and beyond. *Frontiers in Physiology*, 10(Feb). <https://doi.org/10.3389/fphys.2019.00111>
- Supej, M., Kipp, R., & Holmberg, H. C. (2011). Mechanical parameters as predictors of performance in alpine world cup slalom racing. *Scandinavian Journal of Medicine and Science in Sports*, 21(6), 72–81. <https://doi.org/10.1111/j.1600-0838.2010.01159.x>
- Supej, M., Sætran, L., Oggiano, L., Ettema, G., Šarabon, N., Nemeč, B., & Holmberg, H. C. (2013). Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. *Scandinavian Journal of Medicine and Science in Sports*, 23(1), 38–47. <https://doi.org/10.1111/sms.12007>
- Thorwartl, C., Tschopp, A., Lasshofer, M., Holzer, H., Zirkl, M., Hammer, M., Stadlober, B., & Stöggl, T. (2023). Technique-dependent relationship between local ski bending curvature, roll angle and radial force in alpine skiing. *Sensors (Switzerland)*, 23(8), 3997. <https://doi.org/10.3390/s23083997>
- Turnbull, J. R., Kilding, A. E., & Keogh, J. W. L. (2009). Physiology of alpine skiing. *Scandinavian Journal of Medicine and Science in Sports*, 19(2), 146–155. <https://doi.org/10.1111/j.1600-0838.2009.00901.x>
- Vaverka, F., & Vodickova, S. (2010). Laterality of the lower limbs and carving turns. *Biology of Sport*, 27(2), 129–134. <https://doi.org/10.5604/20831862.913080>
- Vaverka, F., Vodickova, S., & Elfmark, M. (2012). Kinetic analysis of ski turns based on measured ground reaction forces. *Journal of Applied Biomechanics*, 28(1), 41–47. <https://doi.org/10.1123/jab.28.1.41>
- Yoneyama, T. (2018). Variable side-cut ski for a carved turn. *Sports Engineering*, 21(4), 277–282. <https://doi.org/10.1007/s12283-018-0267-0>