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### ABSTRACT

Recently, four concepts explaining time differences in alpine ski racing have been suggested. Since the demands on a "well performed" turn are contradicting among these concepts, it is unclear which turn characteristics a skier should aim for in a specific giant slalom situation. During a video-based 3D-kinematic field measurement, single repetitive runs of a world class athlete were compared regarding section times over one turn and variables explaining time differences. None of the existing concepts was able to entirely explain time differences between different performed turns. However, it was found that the skier's line and timing played an important role for time over short sections. Hence, for both science and coaching, there is a need for more comprehensive approaches that include all variables influencing performance in one concept. In coaching, one such approach could be the training of implicit adaptation mechanisms in terms of situation-dependent line and/or timing strategies.

**Key words:** Alpine Ski Racing, Giant Slalom, Kinematics, Section Times

## INTRODUCTION

Alpine ski racing is a highly developed sport in terms of business and training concepts. However, there is still a lack of functional and biomechanical understanding of the performance relevant parameters. Only a limited number of studies have used a comprehensive biomechanical approach to investigate the influence of skier's actions and tactics on performance.[1-7] By rules, performance is defined as the shortest time from start

line to finish line.[8] In contrast, a high section performance can have different meanings: a short section time, a high velocity exiting the section, high velocity gain (exit velocity – entrance velocity) or low energy dissipation over the section. Since section performance also depends on the performance in the previous section,[6] in some cases, even a lower section performance may be advantageous if it results in a disproportionately higher performance in the following section.

Regarding section time as the parameter of performance, recently, four basic concepts explaining time differences have been suggested in science and/or coaching: 1) entrance velocity; 2) path length; 3) energy dissipation; and 4) the theoretical concept of the "quickest path of descent". A first explanation for shorter section times could be higher entrance velocities.[6] On the one hand, for consecutive sections, this would mean that a skier should aim for high section exit velocities in order to increase the performance of the following sections. On the other hand, there also might be a kind of "velocity barrier" above which the athlete needs to control speed to avoid mistakes,[6] which limits this strategy markedly. A second explanation could be the common coaches' doctrine that a shorter path length may result in a shorter sector time. However, a shorter path length requires shorter turn radii and may therefore lead to a loss of speed. A third explanation for shorter sector times could be found in lower mechanical energy dissipation $(E_{DISS})$ – calculated as the change in the skier's total mechanical energy per change in meter altitude and mass. $E_{DISS}$ was introduced as a parameter to estimate the quality of a turn and provides information about how much energy is lost due to snow friction and air drag.[9] Consequently, the difference in total mechanical energy per mass and entrance velocity $(\Delta e_{mech}/v_{in})$ was suggested as a predictor of performance in slalom.[6] Based on this parameter, a well performed turn is a turn with the lowest energy dissipation possible in relation to entrance velocity.[6] Since high energy dissipation has been associated with high turning forces, and thus with short turn radii, it was suggested that choosing a smooth round line between the gates would lead to better performance than skiing a more direct line from gate to gate.[6] A fourth explanation for short section times could be found in the theoretical concept that models the centre of mass trajectory (COM line) of the quickest descent in a ski turn. This concept suggests that the fastest line does not have the characteristics of a smooth, round track; rather, it has a shape somewhat similar to the letter Z (Z-trajectory; "short turning-pull out straight").[10-12]

Comparing these concepts, the COM line characteristics, suggested by the concept of the "shortest path length" or the theoretical concept of the "quickest path of descent", contradict the concept of minimizing energy dissipation to increase performance. Moreover, the influence of entrance velocity on section time may depend, due to aspects of the "velocity barrier", on the situation as well.[6] Therefore, it is not *a priori* clear which turn characteristics should be aimed for in a specific giant slalom situation for a high section performance.

The purposes of this case study were threefold. The first purpose was to assess the ability of the aforementioned concepts to explain time differences observed in a one-turn section in a giant slalom course. The second purpose was to compare COM line characteristics of turns with fast and slow section times and to discuss their plausibility to be advantageous. Since course setting varies from race to race in alpine ski racing, a third purpose of this study was to compare turns with fast and slow section times for two different course settings and to assess if similar line characteristics were observable.

## METHOD

A top world-class athlete (world champion in giant slalom within the same year) performed a total of 12 runs on two different course settings. For the first six runs, the vertical gate

distances were 26 m with an offset of 12 m. For another six runs, the offset was changed to 10 m (Fig. 1). A total of 78 reference points, geodetic measured by theodolite, were used to calibrate a capture volume corridor of approximately 52×12×2 m (Fig. 1). In this area, the skier was filmed with a system of five panned, tilted and zoomed cameras (Panasonic F15, 50Hz, 460 line resolution, time synchronized by a gen-lock signal). All runs were recorded in a manner in which the skier covered approximately two-thirds of the picture. In each frame of each camera, a segment model with 28 points on the skier, the skis and the ski poles, as well as the three best visible reference points were manually digitized. The joint centres of the segment model were defined according to de Leva [13]. The skier's 3D position data were reconstructed using the software *PEAK MOTUS* and a DLT-based *PANNING ALGORITHM* by Drenk [14]. Post processing and parameter calculation were performed in the software *MATLAB R2009b*. Collecting kinematic data on a ski track with panning, tilting and zoomed cameras, as was performed in the present study, has been shown to be reliable and comparable to the accuracy under laboratory conditions in an earlier study.[15] The current study was approved by the Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

The COM line was calculated based on the centre mass model of Clauser et al. [16], adjusted for the skiing equipment. Ski line was defined as the trajectory of the midpoint between the ankle joints, projected to the slope plane (x,y-plane). The x-axis was orientated in the direction of the highest gradient on the slope plane (fall line). Line strategies were analysed with regard to timing and placement characteristics of the turn in relation to the gate. For parameter calculation, five characteristic points in COM / ski lines were defined (Fig. 1). The beginning *(a)* and end *(e)* of the turn were determined by the crossing points of the COM line and the ski line projected to the slope plane (x,y-plane), as proposed by Supej et al.[17] The point where COM begins to substantially change its direction (COM turn radius ≤ 30 m) *(b)*, the point of the COM passing the gate *(c)*, and the point where COM stops substantially changing its direction (COM turn radius ≤ 30 m) *(d)* were defined similarly to the definitions of Reid et al.[5] Based on these points, three turn phases were defined (Fig. 1): *Initiation (a→b)*, *COM Direction Change (b→d)*, and *Completion (d→e)*. Moreover, the turn was divided into two sections (Fig. 1): *Pre Gate Section (a→c)* and *Post Gate Section (c→e)*. The turn cycle structure was calculated as the percentage of each turn phase or turn section in relation to the whole turn. The placement of the turn was described as the distance in x- / y-direction from the position of the beginning of the turn to the gate *($\Delta x_a$ / $\Delta y_a$)*, and the distance in x- /- y direction from the end of the turn to the gate *($\Delta x_e$ / $\Delta y_e$)* on the slope plane (Fig. 3).

COM path length *($L_{COM}$)*, COM turn radius *($R_{COM}$)*, and COM speed *(v)* were calculated numerically based on the COM-line using the four- and five-point finite central formulae.[18] Total mechanical energy *($E_{mech}$)* was calculated as the sum of kinetic energy and potential energy. The change in specific mechanical energy per entrance velocity *($\Delta e_{mech}/v_{in}$)*, as a measure for energy dissipation, was calculated according to Supej et al. [6] using finite central differences, eqn (I):

$$\Delta e_{mech}/v_{in} = \frac{\Delta E_{mech}}{m \cdot v_{in}} \tag{I}$$

COM traverse angle *($\beta_{COM}$)* was defined as the angle between the instant direction of COM motion and the fall-line (x-axis) (Fig. 2). Skid angle *($\gamma_{Ski}$)*, as a measure to estimate the degree of skidding, was defined as the angle between ski axis and the instant direction of motion of the ankle joint (velocity vector) of the outer leg (Fig. 2).
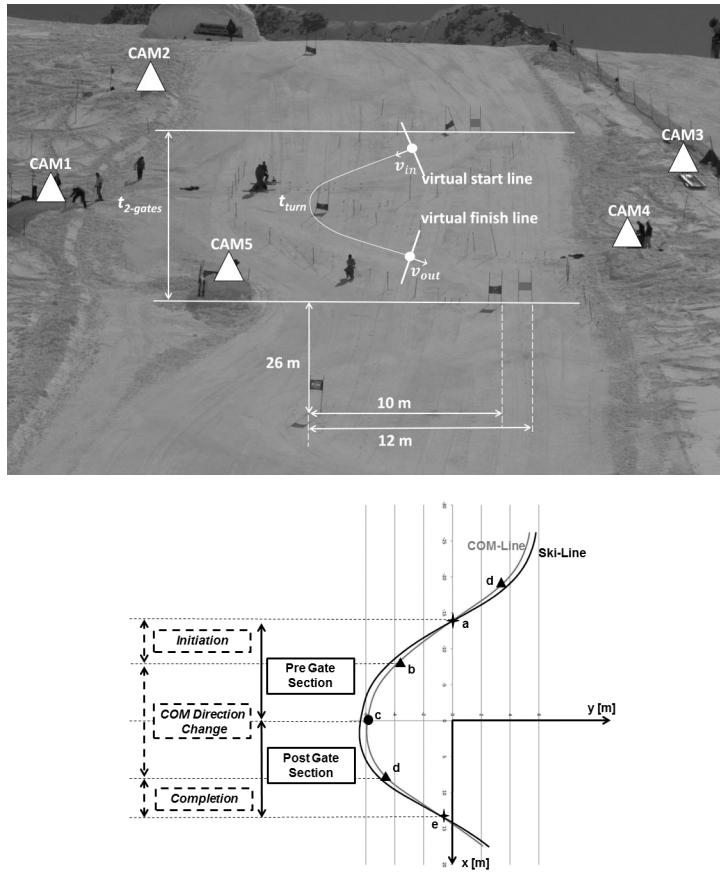
Figure 1. Overview of the Measurement Setup (top)
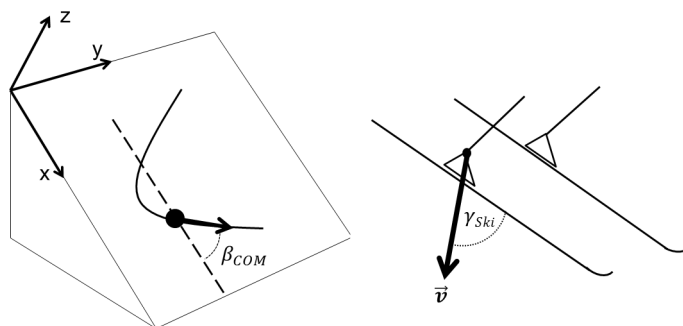Characteristic Line Points and Definition of Turn Phases and Turn Sections
(bottom)



Figure 2. Angle Definitions: COM Traverse Angle ($\beta_{COM}$) (left); Skid Angle
($\gamma_{Ski}$) (right); Velocity Vector (v)

Turn time was defined as the time from the beginning to the end of the turn. Since the actual positions of the starting and end points on the slope plane varied between the runs, virtual start and finish lines were constructed, as suggested by Reid [19]. Start and finish lines were defined by calculating the average COM position and the average direction of the COM velocity vector at the starting / end points of all analysed trials. Next, the lines through the average position on the slope plane and perpendicular to the average velocity vector were used as virtual start and finish lines to calculate $t_{turn}$ (Fig. 1). Entrance speed $(v_{in})$ and exit speed $(v_{out})$ were calculated as the instant values of COM speed while passing the virtual start / finish lines (Fig. 1). Path lengths $(L_{COM})$, as well as the averages of the other performance related parameters (Table 1), were calculated for the section between the virtual start and finish lines. In order to ensure a constant performance over a larger than the analyzed section, times from the last gate contact before the analyzed turn until the next gate contact after the analyzed turn $(t_{2\text{-}gates})$ were determined based on high-speed video (100 Hz) captured from the opposite hillside (Fig. 1).

For assessing the ability of the current concepts to explain time differences, the turn with the fastest $t_{turn}$ on the 26/12 m course was compared to the slowest turn (Table 1). For the comparison of COM line characteristics and turn cycle structures, the two single values of the fastest turns regarding $t_{turn}$ (1st and 2nd ranked) were compared to the two single values of the slowest turns (5th and 6th ranked) (Table 2). The 3rd and 4th ranked turns were not considered for the analysis in order to clearly separate performance groups.

Table 1. Comparison of Turn Characteristics Between the Fastest and the Slowest Trial Regarding $t_{turn}$ on the 26/12m Course: (turn) Average Start to Finish Line; (pre) Average Start Line to Gate; (post) Average Gate to Finish Line

|  | **Fastest Trial** | **Slowest Trial** |
|---|---|---|
| $t_{turn}$ [s] | 1.68 | 1.74 |
| $v_{in}$ [m/s] | 17.58 | 17.29 |
| $v_{out}$ [m/s] | 17.79 | 17.16 |
| $L_{COM}$ [m] | 29.86 | 29.53 |
| $\Delta e_{mech}/v_{in}$ (turn) [Js/kg/m] | -3.96 | -3.96 |
| $\Delta e_{mech}/v_{in}$ (pre) [Js/kg/m] | -4.51 | -5.44 |
| $\Delta e_{mech}/v_{in}$ (post) [Js/kg/m] | -3.37 | -2.81 |
| $\gamma_{Ski}$ (turn) [°] | 12.0 | 12.7 |
| $\gamma_{Ski}$ (pre) [°] | 17.3 | 24.0 |
| $\gamma_{Ski}$ (post) [°] | 6.4 | 3.8 |
| $R_{COM}$ (turn) [m] | 20.57 | 20.13 |
| $R_{COM}$ (pre) [m] | 19.80 | 19.61 |
| $R_{COM}$ (post) [m] | 21.20 | 20.45 |
| $\beta_{COM}$ (turn) [°] | 21.9 | 22.7 |
| $\beta_{COM}$ (pre) [°] | 23.1 | 24.3 |
| $\beta_{COM}$ (post) [°] | 20.6 | 21.4 |

COM: centre of mass; $t_{turn}$: section time from start to finish line; $v_{in}$: entrance velocity at the start line; $v_{out}$: exit velocity at the finish line; $L_{COM}$: Centre of mass path length from start to finish line; $\Delta e_{mech}/v_{in}$: difference in mechanical energy divided by entrance velocity; $\gamma_{Ski}$: Skid Angle of the outside ski; $R_{COM}$: Centre of mass turn radius; $\beta_{COM}$: Centre of mass traverse angle.

Since using time to define performance over short sections is limited by the performance of the previous section and, therefore, by the entrance velocity,[6] a correlation analysis was performed. In order to critically discuss $t_{turn}$ as a parameter for performance definition in the current study, Spearman's rank correlation between $t_{turn}$ and $t_{2\text{-}gates}$, $t_{turn}$ and $v_{in}$, and $v_{in}$ and $v_{out}\text{-}v_{in}$ was calculated. A $p$-value of 0.05 was chosen as the level of statistical significance.

## RESULTS
### COMPARISON OF THE FASTEST VS. SLOWEST TURN ON THE 26/12 m COURSE REGARDING PARAMETERS EXPLAINING TIME DIFFERENCES

The parameters explaining the differences in section time between the fastest and the slowest trial on the 26/12 m course are presented in Table 1. The fastest and the slowest trial on the 26/12 m course differed 3.6% in $t_{turn}$. $L_{COM}$ from the start to the finish line was 1.1% longer for the fastest trial. Entrance velocity ($v_{in}$) was 1.7% higher, and exit velocity ($v_{out}$) was 3.7% higher for the fastest trial. The change in velocity from entrance to exit was +0.21 m/s for the fastest and -0.13 m/s for the slowest trial. For $\Delta e_{mech}/v_{in}$, the turn average (start to finish line) was the same for both trials, whereas there was a 20.6% lower value for the pre gate average and a 16.6% higher value for the post gate average in the fastest trial. A similar trend regarding turn sections was found for $\gamma_{Ski}$, although in total, there was a 5.8% lower turn average (start to finish line) in the fastest trial. $R_{COM}$ was larger and $\beta_{COM}$ was smaller throughout the turn in the fastest trial. The largest differences between the fastest and the slowest trial regarding performance relevant parameters were found in the pre gate average and post gate average for $\Delta e_{mech}/v_{in}$ and $\gamma_{Ski}$, whereas in turn average (start to finish line), similar values for these parameters were observed.
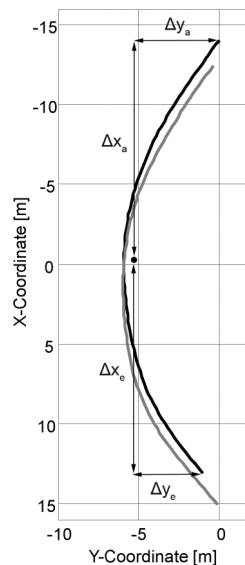


Figure 3. a) Comparison of COM Lines Between the Fastest and Slowest Trial Over One Turn Cycle at the 26/12m Course Setting (black: fastest, grey: slowest)

## COMPARISON OF THE FASTEST VS. SLOWEST TRIAL ON THE 26/12 m COURSE REGARDING COM LINE CHARACTERISTICS AND TURN CYCLE STRUCTURE

Comparing the COM line characteristics on the 26/12 m course, the fastest turn was initiated 1.60 m and terminated 1.98 m higher on the slope plane regarding the distance to the gate in x-direction ($\Delta x_a$ / $\Delta x_e$) than the slowest turn (Fig. 3). $\Delta y_a$ was 0.39 m greater and $\Delta y_e$ was 0.94 m smaller in the fastest turn (Fig. 3). The fastest turn had a 2.5% longer *Initiation*, a 1.2% longer *COM Direction Change*, a 3.7% shorter *Completion* and an 8% longer *Pre Gate Section* (Fig. 4).
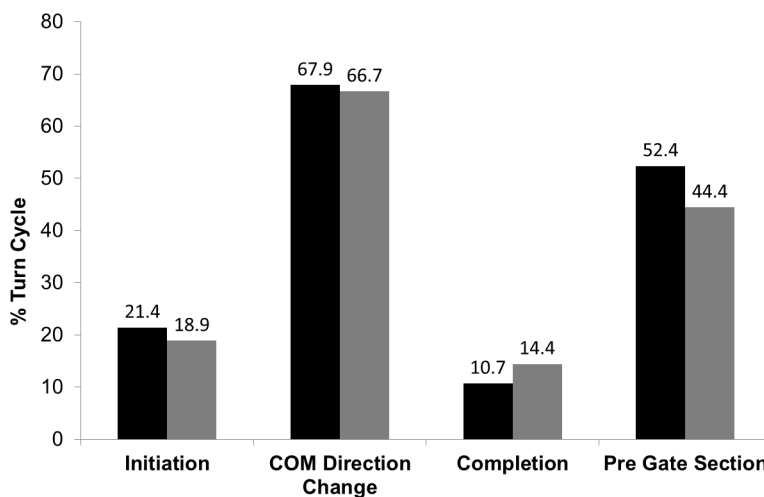


Figure 4. Comparison of Turn Cycle Structures Between the Fastest and the Slowest Trial at the 26/12m Course Setting (black: fastest, grey slowest)
For turn phase / section definition, see Figure 1.

## COMPARISON OF FAST VS. SLOW TRIALS FOR TWO DIFFERENT COURSE SETTINGS REGARDING COM LINE CHARACTERISTICS AND TURN CYCLE STRUCTURE

COM line characteristics and turn cycle structure of the two fastest and the two slowest trials for two different course settings are presented in Table 2. Fast trials (1st and 2nd regarding $t_{turn}$) differed from slow trials (5th and 6th regarding $t_{turn}$) by not less than 0.04 s for the 26/12 m course and not less than 0.02 s for the 26/10 m course. This is a 2.3% difference for the 26/12 m course, and a 1.2 % difference for the 26/10 m course.

Regarding x-direction, fast turns were initiated farther from the gate and were terminated nearer the gate at both course settings. The differences of $\Delta x_a$ between single values of fast and slow trials were not less than 0.45 m for the 26/12 m course, and not less than 1.13 m for the 26/10 m course. The differences of $\Delta x_e$ between the single values of fast and slow trials were not less than 0.30 m for the 26/12 m course, and not less than 0.05 m for the 26/10 m course. Regarding the distance in y-direction ($\Delta y_a$, $\Delta y_e$) for both course settings, fast turns were initiated farther from the gate and terminated closer to the gate than slower turns. The differences of $\Delta y_a$ between the single values of fast and slow trials were not less than 0.06 m

Table 2. Comparison of Fast vs. Slow Trials for Two Different Course Settings Regarding COM Line Characteristics and Turn Cycle Structure

| | 26/12 m course | | 26/10 m course | |
| --- | --- | --- | --- | --- |
| | Fast Trials (1st / 2nd) | Slow Trials (5th / 6th) | Fast Trials (1st / 2nd) | Slow Trials (5th / 6th) |
| $t_{turn}$ [s] | 1.68 | 1.72 | 1.68 | 1.70 |
| | 1.68 | 1.74 | 1.68 | 1.70 |
| $\Delta x_a$ [m] | -14.06 | -13.39 | -14.34 | -13.21 |
| | -13.84 | -12.46 | -14.95 | -13.21 |
| $\Delta x_e$ [m] | 13.00 | 13.31 | 12.32 | 12.86 |
| | 13.01 | 14.98 | 12.36 | 12.41 |
| $\Delta y_a$ [m] | 5.66 | 5.51 | 5.19 | 4.80 |
| | 5.57 | 5.27 | 5.00 | 4.64 |
| $\Delta y_e$ [m] | 4.63 | 5.14 | 4.58 | 4.57 |
| | 4.70 | 5.57 | 4.40 | 4.74 |
| Initiation [%] | 21.4 | 20.9 | 24.1 | 22.2 |
| | 22.6 | 18.9 | 25.3 | 22.2 |
| COM Direction Change [%] | 67.9 | 61.6 | 57.8 | 60.5 |
| | 61.9 | 66.7 | 56.6 | 60.5 |
| Pre Gate Section [%] | 52.4 | 48.8 | 53.0 | 49.4 |
| | 50.0 | 44.4 | 54.2 | 50.6 |
| Completion [%] | 10.7 | 17.4 | 18.1 | 17.3 |
| | 15.5 | 14.4 | 18.1 | 17.3 |

COM: centre of mass; 1st: first ranked trial; 2nd: second ranked trial; 5th: fifth ranked trial; 6th: sixth ranked trial; $t_{turn}$: section time from start to finish line; $\Delta x_a$: position on the slope plane in x-direction at the beginning of the turn; $\Delta x_e$: position on the slope plane in x-direction at the end of the turn, $\Delta y_a$: position on the slope plane in y-direction at the beginning of the turn; $\Delta y_e$: position on the slope plane in y-direction at the end of the turn.

for the 26/12 m course, and not less than 0.20 m for the 26/10 m course. The differences of $\Delta y_e$ between the single values of fast and slow trials were not less than 0.44 m for the 26/12 m course. At the 26/10 m course the performance groups overlapped slightly.

Fast turns showed a longer *Initiation* for both course settings, whereas the percentage values were higher and the differences to slow turns were greater on the 26/10 m course. Regarding *Initiation*, the differences between the single values of fast and slow trials were not less than 0.5% for the 26/12 m course and 1.9% for the 26/10 m course. Single values of *COM Direction Change* were not less than 2.7% smaller in fast trials on the 26/10 m course, while there were no clear differences between the single values of fast and slow trials found for the 26/12m course. *Pre Gate Section* was longer for fast turns at both course settings: the differences between the single values of fast and slow trials were not less than 1.2% for the 26/12m course, and not less than 2.4% for the 26/10m course. Regarding *Completion*, the differences between fast and slow trials for the 26/10 m course were not less than 0.8%, while there were no clear group differences observed at the 26/12 m.

## RELATIONSHIPS AMONG PARAMETERS DEFINING PERFORMANCE
The relationships among parameters defining performance are presented in Table 3. For both course settings a positive relationship between $t_{turn}$ and $t_{2\text{-}gates}$ was found. While $t_{turn}$ was explainable by $v_{in}$ only to 1.5% ($r^2 = 0.015$) on the 26/12 m course, there was a negative

relationship between $t_{turn}$ and $v_{in}$ on the 26/10 m course. Between $v_{in}$ and $v_{out}$-$v_{in}$, a negative relationship was found for both course settings.

### Table 3. Spearman's Rank Correlation Coefficients for the Parameters Defining Performance

| | 26/12 m course | | | | 26/10 m course | | |
|---|---|---|---|---|---|---|---|
| | $t_{2\text{-}gates}$ | $v_{in}$ | $v_{out}$-$v_{in}$ | | $t_{2\text{-}gates}$ | $v_{in}$ | $v_{out}$-$v_{in}$ |
| $t_{turn}$ | 0.984** | -0.123 | | $t_{turn}$ | 0.894* | -0.828* | - |
| $v_{in}$ | | | -0.771 | $v_{in}$ | - | - | -1.000** |

*$p<0.05$; **$p<0.01$; ***$p<0.001$; $t_{turn}$: section time from start to finish line; $t_{2\text{-}gates}$: times from the last gate contact before the analyzed turn until the next gate contact after the analyzed turn; $v_{in}$: entrance velocity at the start line; $v_{out}$: exit velocity at the finish line.

## DISCUSSION

The main findings were: 1) none of the four current performance prediction concepts was able to give a singular explanation for the difference in section time between the fastest and the slowest turn; 2) differences were found in COM line characteristics and turn cycle structures between trials with fast and slow section times; 3) similar COM line characteristic and turn cycle structure differences were found between trials with fast and slow section times for two different course settings representing both extremes of the course setting spectrum.

### COMPARISON OF THE FASTEST VS. SLOWEST TURN ON THE 26/12 m COURSE REGARDING PARAMETERS EXPLAINING TIME DIFFERENCES
#### Performance Difference
In the current study, a difference of 3.6% in $t_{turn}$ between the fastest and the slowest trial was found within the same athlete (Table 1). Time differences for short sections between different athletes in World Cup competitions were reported to vary by 10%.[20] Knowing that over an entire race course, differences of hundredths of a second often determine who wins a race the potential that improvements in sector time might affect the outcome of a race is quite high.

#### Explanation 1: Entrance Velocity
In the example of the fastest and the slowest turn on the 26/12m course, $v_{in}$ was slightly higher for the fastest trial (Table 1); thus, it could have been influencing performance. However, it is not the sole determinant in our example. Even if entrance velocity ($v_{in}$) had been maintained over the whole path length of the turn ($L_{COM}$), it only would explain 0.01s of the 0.06 s difference in $t_{turn}$.

#### Explanation 2: Path Length
A shorter path length does not serve as an explanation for the differences in section time between the fastest and the slowest trial on the 26/12 m course (Table 1). One reason for this finding could be that the advantages of a shorter COM line do not compensate for the costs concerning energy losses due to snow friction while following this track. Another reason could be that a direct line at one gate may result in a longer line at the next gate. Hence, the costs of a more direct line would be paid at the next gate; therefore, this strategy is intuitively avoided by the athlete. This argument is in line with the findings of Lešnik and Zˇvan [3].

*Explanation 3: Energy Dissipation*

Comparing the fastest and slowest turn on the 26/12 m course, there is no difference regarding $\Delta e_{mech}/v_{in}$ turn average, while $t_{turn}$ differs 3.6% (Table 1.) Surprisingly, it is possible to reach a higher performance despite the same energy dissipation throughout the turn. This indicates that $\Delta e_{mech}/v_{in}$ alone cannot predict performance in every case. A first reason for the observed phenomenon could be that even fast skiers will need to dissipate excess kinetic energy at certain time points.[5] There might be a kind of "velocity barrier" above which the athlete needs to control speed to avoid mistakes.[6] A second reason could be that this concept, due to its simplifications, is only applicable for larger differences such as technical mistakes or differences between athletes,[6] but is not sensitive for smaller differences, like different strategies used by one athlete. A third reason could be found in the distribution of energy dissipation over the turn sections. At the fastest trial, $\Delta e_{mech}/v_{in}$ was lower in the pre gate section, and higher in the post gate section (Table 1). A similar distribution for the turn sections was found for $\gamma_{Ski}$ (Table 1). For a short section time, less energy dissipation / drifting and, therefore, higher velocity at the beginning of the turn may be more advantageous, since this high velocity is acting over a longer part of the turn.

*Explanation 4: "Path of the Quickest Descent"*

The concept of the "path of the quickest descent" [10-12] illustrates, similar to the "brachistochrone problem" in physics, that the question of when and how much potential energy is transformed into kinetic energy within a certain part of the turn, is one key for time optimization. Under the assumption of neglecting energy dissipation due to snow friction, the driving component of gravitational force and, therefore, the transformation of potential energy into kinetic energy, mainly depends on the traverse angle [21]: the smaller the angle, the closer the direction of motion to the fall line and, therefore, the higher the transfer rate of potential energy into kinetic energy. Comparing the fastest and the slowest trial at the 26/12m course, $\beta_{COM}$ is smaller throughout the turn (Table 1). This implies that the acceleration due to gravity is higher over the whole turn for the fastest trial and can be explained by the line characteristic of turning less out of the direction (Fig. 3). However, $R_{COM}$ was constantly larger throughout the turn at the fastest trial. This does not indicate a more pronounced strategy of a Z-trajectory ("short turning - pull out straight"), which was suggested to be the fastest line.[10-12] One explanation for this finding could be that this concept neglects snow friction; therefore, it is only partly applicable for skiing in reality.

*Summary*

This example shows the limitations of the existing concepts of performance enhancement to explain performance differences in section times. In order to give effective advice regarding performance enhancement, they would have to be balanced among each other. Therefore, there is an evident need for improvement of the existing concepts by combining them into one comprehensive concept explaining performance differences.

*COMPARISON OF FAST VS. SLOW TRIALS REGARDING COM LINE CHARACTERISTICS AND TURN CYCLE STRUCTURE*

Comparing the fastest and the slowest trial at the 26/12 m course turns differed in the placement of the COM line in relation to the gate and the timing within the turn cycle. The fastest turn was initiated and terminated higher regarding the vertical position on the slope plane and was turning less out of the direction of the fall line at the end of the turn (Fig. 3). Consequently, a higher percentage of the turn was executed before passing the gate in the

fastest turn, and the *Initiation* was prolonged while the *Completion* was shorter (Fig. 4). Similar COM line and turn cycle differences were observed for other trials and both course settings (Table 2).

These findings are in line with the observations of Nachbauer [1], who found that a high initiation and a high termination of the turn are related to a reduction of time. In contrast to Nachbauer [1], the findings of this study indicate that a longer, not a shorter, initiation phase resulted in the best performance. This may be explained either by the different definition of the turn phases (kinetic vs. kinematic criteria), or the fact that due to the present day side cut of the ski, there are more possibilities to adapt timing by sharper turns after an elongated initiation. The observed differences in COM line characteristics and turn cycle structure seem likely to be related to short section time. As demonstrated on the example of the fastest and the slowest trial on the 26/12 m course, a higher initiation and termination of the turn needs less drifting ($\Delta_{Ski}$) and provokes less energy dissipation ($\Delta e_{mech}/v_{in}$) prior to the gate (Table 1).

## METHODOLOGICAL CONSIDERATIONS
### Single-Subject Analysis
One limitation of the current study might be that only one subject was used. This limits the possibilities of generalising the study findings. However, there are two reasons why a single-subject-design may be a reasonable alternative approach to a group-design for the current research question. First, it is known that, due to differences in athletes' strengths, technical abilities or tactical reasons, different individual strategies can lead to the same performance. In this case it is problematic to conclude "the average" of different athletes (group performance) to be the best strategy for every individual.[22] Second, especially in high performance sports, effective learning strategies are mainly focused on individuals.[23]

### Single-Gate-Analysis
Another limitation of the current study might be that a single-gate-analysis neglects tactical aspects regarding the choice of line down a course. Depending on the course setting before and after the analyzed section, there might be different demands on a well performed turn than a short section time. However, to detect the small, yet substantial differences at top level ski racing, a high degree of accuracy is needed, and the use of video-based 3D kinematics, is indispensable.[15, 24] This limits the capture volume to 1 giant slalom turn.

### Performance Definition
A third limitation of the current study might be to define section time as a performance measure for short sections. This measure is influenced by the performance in the previous section and has the following drawbacks:[6] 1) section time is influenced by the skier's initial velocity, position and orientation; 2) a mistake close to the end has only a small impact on the analyzed section; and 3) high exit velocity, as well as the skier's position and orientation at the end of the turn has marginal influence on the analyzed section, but may be important for the following section.

In the current study there was for both course settings a strong positive relationship between $t_{turn}$ and $t_{2\text{-gates}}$ and negative relationship between $t_{turn}$ and $v_{in}$ on the 26/10 m course (Table 3). Therefore, it is plausible that the performance of the skier was relatively constant over a wide section  and there might be only a marginal influence of entrance velocity on section time on the 26/12 m course. In contrast, on the 26/10 m course which is turning less out of the direction of the fall line, there might be a more substantial influence.

An alternative would have been to use a section performance measure which is normalized with $v_{in}$ instead of section time, as it was recently suggested.[6] However, in the current study, there was a negative correlation between $v_{in}$ and $v_{out}$-$v_{in}$ for both course settings (Table 3). This means that trials with low entrance velocity are gaining disproportionately more velocity throughout the turn. Therefore, it is questionable whether normalization with entrance velocity would have been an improvement for the problem of performance definition over short sections in our study.

## CONCLUSION

This article illustrates the challenge for both scientists and coaches to understand the very complex relationship between parameters underlying performance in alpine ski racing. One reason for this problem might be the fact that the definition of a well performed turn may have different meanings depending on the skiing situation. Another reason might be that the current performance prediction concepts address only one aspect of a very complex relationship. In the specific case studied here, the line and/or timing aspects were critical for decreasing the turn time. Future scientific work and coaching should aim for more comprehensive approaches which consider all variables influencing performance in one concept. In science, looking at instantaneous performance rather than at section performance, as recently suggested by Federolf [25], may open new possibilities of combining different variables related to performance at the same time. In coaching, the training of the implicit adaptation mechanisms in terms of situation depending line and/or timing strategies may be an alternative approach to address different variables influencing performance at the same time.

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