Kinetic Analysis of Ski Turns
Based on Measured Ground Reaction Forces

Frantisek Vaverka,¹ Sona Vodickova,² and Milan Elfmark³
¹University of Ostrava; ²Technical University of Liberec; ³Palacky University

The objective of this study was to devise a method of kinetic analysis of the ground reaction force that enables the durations and magnitudes of forces acting during the individual phases of ski turns to be described exactly. The method is based on a theoretical analysis of physical forces acting during the ski turn. Two elementary phases were defined: (1) preparing to turn (initiation) and (2) actual turning, during which the center of gravity of the skier–ski system moves along a curvilinear trajectory (steering). The starting point of the turn analysis is a dynamometric record of the resultant acting ground reaction force applied perpendicularly on the ski surface. The method was applied to six expert skiers. They completed a slalom course comprising five gates arranged on the fall line of a 26° slope at a competition speed using symmetrical carving turns (30 evaluated turns). A dynamometric measurement system was placed on the carving skis (168 cm long, radius 16 m, data were recorded at 100 Hz). MATLAB procedures were used to evaluate eight variables during each turn: five time variables and three force variables. Comparison of the turn analysis results between individuals showed that the method is useful for answering various research questions associated with ski turns.

Keywords: alpine skiing, dynamometry, kinetics, ski turn phases

It is possible to separate a single run during alpine skiing into linear motion and turns. The speed during linear motion is only significant in ski racing, and requires consideration of aerodynamic forces (Barelle et al., 2004). In contrast, the ski turn is a fundamental element for speed regulation in both sport and race skiing, and it is the focus of both practice and research. One of the basic problems is dividing a turn into its individual phases. Ski turns performed during alpine skiing are commonly divided into individual phases based on kinematic data or the dynamometric measurements of reaction forces from verbal descriptions of skiing behaviors. In the literature, a turn is commonly divided into the initiation phase (turn initiation) and the steering phase (turn steering). However, the actual separation into these phases varies with the subjective opinions of different authors and the descriptions of the ski positions and skier movements. Berger (1989), Chevalier (1996), and Müller and Schwameder (2003) divided a ski turn into three phases, whereas Kriechbaum (1993) described only two turn phases. Subsequent work has focused on comparing carving and traditional turns, with division into initiation and steering phases (Müller et al., 2005), and kinematic analysis and verbal and subjective descriptions of the particular processes occurring during the turn (Berger, 1989; Kriechbaum, 1993; LeMaster, 2007). Some kinematic analyses of ski turns have been combined with measurements of the reaction forces acting on skis (Nachbauer & Rauch, 1991; Raschner, 1997; Raschner et al., 1999; Schwameder et al., 2001; Müller & Schwameder, 2003; Müller et al., 2005; Fauve et al., 2007). These reports use the same verbal description of the various turn phases based on changes in ski loadings. Müller et al. (1998) significantly contributed to precisely defining the phases of the ski turn (initiation, steering I, and steering II) based on kinematic analysis of selected positions of the body segments. Similarly, Supej et al. (2002) defines the termination of the turn (which simultaneously means the start of a new turn) with the aid of a kinematic analysis on the basis of the intersection of trajectory of the center of gravity of the body and that of the skis’ axis. Supej (2008) describes the motion of a competitor ski racer based on the change in the mechanical energy of the skier based on a kinematic analysis of the motion. Technologies that allow real data to be collected for complex analyses of a skier’s motion in 3D are entering the research field of skier...
movement. These systems include those based on GPS monitoring of the skier’s location (Brodie et al., 2008) or technology based on combining an inertial-sensor motion-capture suit and a GNSS RTK system (Brodie et al., 2008; Supej, 2010). Although these approaches can be used to monitor the complex movement of the skier, they do not directly address the analysis of the particular phases of the turn.

The evaluation of ski-turn phases and the basing of kinematic analyses of turn duration on the subjective opinions of authors means that objective comparable data cannot be acquired. However, the phases of a ski turn can be exactly defined using a biomechanical approach in terms of the physical forces acting on the system, which in principle allows for exact criteria to be used to define them. Consider the motion during turning as the center of gravity of the skier–ski system moving along a curvilinear trajectory with a centrifugal force acting—this phase is described as the steering (STE) phase. In contrast, the motion between turns and all movements leading to the turn initiation is called the initiation (INI) phase.

The purpose of the study was to define the elementary INI and STE phases of a ski turn by analyzing the external forces acting on the system during turning. Such a physical definition of these two basic turn phases forms the basis of developing a method of kinetic analysis for the acting ground reaction force as measured dynamometrically.

## Methods

### Theoretical Basis

Biomechanical analysis of the forces acting during a ski turn leads to new methods for analyzing the ski turn in terms of time and force. The following theoretical standpoints are derived from the concept of biomechanics in skiing presented by Howe (1983), who considered three groups of forces that influence the movement of the skier in straight gliding. The force of gravity acts on the total body mass of the skier with his/her equipment \((F_g = m \cdot g)\), where \(m\) is the mass of the skier, and \(g\) is the acceleration due to gravity, where \(g = 9.81 \text{ m/s}^2\), the forces acting against the movement of the skier, so-called resistive forces (friction sliding \(F_w\), aerodynamic drag \(F_{w_d}\), and braking force \(F_b\) acting at the contact between the skis and the ground), and dynamic force \(F_d\), which is connected to the muscle activity of the skier and accelerates his/her movement (e.g., when poling or skating) are also neglected.

During the turn movement, the fictitious centrifugal force \(F_C\) can be considered within the above-mentioned set of forces. This force may be treated algebraically as a real centripetal force producing the curvature of the turn. The magnitude of \(F_C\) depends on the mass of the skier \(m = F_g / g\), the speed of the movement \((V)\), and the radius of turning \((r)\):

\[
F_C = \frac{F}{g} \cdot \frac{V^2}{r}
\]

The centrifugal force acts mainly parallel to the ground in the direction of a straight line going outside the turn through the center of turning. This considers the lateral direction of the acting force (Figure 1). It simultaneously acts on so-called lateral force \(F_{LA}\) lying in the same straight line as the centrifugal force (Howe, 1983). The magnitude of \(F_{LA}\) depends on the magnitude of the force of gravity \((F_g)\), on the inclination of the slope \((\alpha)\), and deviation \(F_{LA}\) from the direction of acting force \(F_g\) \(\sin(\alpha)\) expressed by angle \(\beta\). Resultant force \(F_{TL}\) in the lateral direction is given by the summation of centrifugal force \(F_C\) and lateral force \(F_{LA}\):

\[
F_{TL} = F_C \pm F_{LA}
\]

The plus/minus sign allows for \(F_{LA}\) to be subtracted from centrifugal force \(F_C\) during the phase of the turn that occurs above the level of the contour line (uphill quadrants), and to be added to \(F_C\) during the phase of the turn under the contour line (downhill quadrants) (Figure 1). Inserting other variables and modifying yields the equation for the magnitude of lateral force \(F_{TL}\):

\[
F_{TL} = \frac{F_g}{g} \cdot \frac{V^2}{r} \pm F_g \cdot \sin(\alpha) \cdot \cos(\beta)
\]

Resultant reaction force \(R\) acting on the skier is given by the vector sum of the perpendicular component of the force of gravity to the ground, \(F_g \cos(\alpha)\), and the resulting lateral force, \(F_{TL}\):

\[
R = \sqrt{\left(\frac{F_g}{g} \cdot \frac{V^2}{r} \pm F_g \cdot \sin(\alpha) \cdot \cos(\beta)\right)^2 + \left(F_g \cdot \cos(\alpha)\right)^2}
\]

It is important to understand the difference between the concept of a “ski turn” in terms of skiing and in terms of the physical standpoint during this phase.

From a physical point of view, the turn constitutes a movement where the center of gravity of the skier moves along a curvilinear line and the magnitude of subsequent lateral force \(F_{TL}\) is positive; in other words, resultant R is larger than the force acting perpendicular to the ground, \(F_g \cos(\alpha)\) (Figure 2).
Criterion for Dividing Turns Into Phases

We can use the above biomechanical considerations to define the following two phases of a turn:

1. **INI phase**, which consists of all movements of the skier leading to the beginning of the turn. During this phase the center of gravity of the skier moves on a straight line, \( F_{TL} = 0 \), and \( R \leq F_g \cos(\alpha) \).

2. **STE phase**, which is the actual turning process. During this phase the center of gravity of the skier moves on a curved line, \( F_{TL} > 0 \), and \( R > F_g \cos(\alpha) \).

The above concepts are supported by conclusions of Howe (1983), who stated that as long as subsequent lateral force \( F_{TL} \) acts in the center of the turn or equals zero (\( F_{TL} = 0 \)), it can be considered to be a phase of preparation for a further turn, which starts at the moment that resulting force \( F_{TL} \) begins to act outside of the center of the turn (\( F_{TL} > 0 \)).

Dynamometry of a Skiing Turn

The starting point of our kinetic analysis method of ski turns is a dynamometric record of the resultant forces acting on the skier. The inner muscle forces influence the pressure of the skis on the ground, and the characteristics of the interaction between the skis and the ground (e.g., snow and ice produce different interactions) determines the reaction forces that are measured using dynamometry.

The sum of partial reaction forces acting on the left and right legs perpendicular to the plane of the skis creates final reaction force \( R \) that acts on the skier. The magnitude of \( R \) is given by the vector sum of the measured forces acting on the left and right lower extremities (Figure 2).
The value of \( R \), equal to the measured \( F_Z(t) \), is the starting point for the presented methodology. A dynamometric system of our own construction was used to measure the reaction forces in alpine skiing. The facilities were developed and verified at the Technical University of Liberec, Czech Republic, and are described in detail in Vodickova et al. (2004, 2005). The recording apparatus was placed on 168-cm-long carving skis (Blizzard SLK) with a radius of 16 m. A system of eight strain gauges on each ski with the same size as a carving plate was mounted under the boot bindings. The measuring system simultaneously recorded the magnitude of reaction forces acting in the mediolateral, anteroposterior, and perpendicular directions to the plane of the ski, and also the force moments acting in these three directions. In our methodology the perpendicular component of the ground reaction force \( F_Z(t) \) was used. The obtained forces data were low-pass filtered at 10 Hz. A small bag containing data-recording equipment and weighing 0.5 kg was fixed to the lower part of the skier’s back close to the center of gravity of the body. Data were recorded at 100 Hz. The measurement error of this system was less than 3%.

The dynamometrically measured reaction force, \( F_Z(t) \), shown in Figure 3A corresponds to the mathematical summation of the reaction forces acting on the right and left legs (Figure 3B). The criterion for the division into the INI and STE phases of the ski turn is based on the formula \( R \leq F_g \cos(\alpha) \) and \( R > F_g \cos(\alpha) \). The INI phase occurs when the reaction force is less than or equal to this value, and the STE phase occurs when the reaction force exceeds this value. In a graphical representation, the line given by \( F_g \cos(\alpha) \) divides each turn into the INI and STE phases that form the basis for calculating time and force variables (Figures 3 and 4). The results of the kinetic analysis of the ski run of one participant (No. 3, \( m = 85 \) kg, slope angle inclination \( \alpha = 26^\circ \), and \( F_g \cos(\alpha) = 751 \) N) in five joined carving turns are presented in tabular form in Figure 3C.

![Figure 3](image-url)
Description of the Experiment

The proposed methods were verified by performing experiments involving six experienced skiers (three members of a national ski-racing team and three professional instructors, mean ± SD: age 26.5 ± 1.61 years, height 1.80 ± 0.04 m, and mass 88.83 ± 5.46 kg) skiing through a symmetrical slalom course (five gates) arranged on the fall line. Mass consists of skier’s body and equipment. The experimental subjects were asked to complete the course at competition speed using symmetrical connected carving turns. A slalom course was constructed in the direction of the fall line, where the distance between the gates was 14 m and the parallel distance between the gates was 4 m. Five turns performed during one ski run were evaluated for each skier (3 left turns and 2 right turns), giving a total of 30 turns for the analysis. The ground had a slope of $\alpha = 26^\circ$, and the criterion for dividing the turn into phases INI and STE for all subjects was calculated using

$$ F_g \cdot \cos(\alpha) = m g \cos(26^\circ) = m 8.83. $$

We used mathematical modules in MATLAB to evaluate the defined variables. Statistical analysis (mean, standard deviation, coefficient of variation, minimum, maximum, and Kolmogorov–Smirnov test) was performed using STATISTICA (version 6).

Results

The suggested method of kinetic analysis of ski turns employs eight variables: five time variables and three force variables. The durations of the ski turn and its phases are expressed in seconds, and the proportion of each turn phase relative to the total turn duration is expressed as a percentage. The force conditions during a given turn are characterized by the magnitudes of the maximum force, average force, and force impulse in the STE phase (Figure 3, Table 1).

Figure 4 — Graphical depiction of force variables.

Statistical analyses were performed by the data obtained for 30 turns. Despite the small number of analyzed turns, the Kolmogorov–Smirnov test showed that all variables conformed to a normal data distribution. The proportions of the INI and STE phases relative to the total turn duration were 36 ± 7% and 64 ± 7%, respectively; the mean magnitude of the maximum force ($F_M$) was 2244 N, the mean value of average reaction force ($F_A$) was 1537 N, and the mean value of force impulse ($F_I$) was 649 N·s (Table 1). The coefficient of variation of the time variables (excluding the initiation time of the turn, $t_{INI}$) and force variables (excluding $F_I$) was about 20; these two excluded variables demonstrated larger variability.

Statistical comparisons of measured variables in individual skiers revealed interindividual differences (Table 2). The average turn duration provides indirect information about speed. The turn duration was shortest

<table>
<thead>
<tr>
<th>Variable</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>CV</th>
<th>Min</th>
<th>Max</th>
<th>K-S test</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{INI}$ (s)</td>
<td>30</td>
<td>0.487</td>
<td>0.119</td>
<td>24</td>
<td>0.300</td>
<td>0.740</td>
<td>*</td>
</tr>
<tr>
<td>$t_{STE}$ (s)</td>
<td>30</td>
<td>0.858</td>
<td>0.163</td>
<td>19</td>
<td>0.540</td>
<td>1.180</td>
<td>*</td>
</tr>
<tr>
<td>$t_{TOT}$ (s)</td>
<td>30</td>
<td>1.344</td>
<td>0.210</td>
<td>16</td>
<td>0.980</td>
<td>1.680</td>
<td>*</td>
</tr>
<tr>
<td>$t_{INI}$%</td>
<td>30</td>
<td>36.23</td>
<td>6.84</td>
<td>19</td>
<td>20</td>
<td>50</td>
<td>*</td>
</tr>
<tr>
<td>$t_{STE}$%</td>
<td>30</td>
<td>63.77</td>
<td>6.84</td>
<td>11</td>
<td>50</td>
<td>80</td>
<td>*</td>
</tr>
<tr>
<td>$F_M$ (N)</td>
<td>30</td>
<td>2244</td>
<td>511.4</td>
<td>23</td>
<td>1114</td>
<td>3612</td>
<td>*</td>
</tr>
<tr>
<td>$F_A$ (N)</td>
<td>30</td>
<td>649</td>
<td>282.2</td>
<td>44</td>
<td>125</td>
<td>1099</td>
<td>*</td>
</tr>
<tr>
<td>$F_I$ (N·s)</td>
<td>30</td>
<td>1537</td>
<td>299.5</td>
<td>19</td>
<td>961</td>
<td>1999</td>
<td>*</td>
</tr>
</tbody>
</table>


*Data conform to a normal distribution.

Table 1 Basic statistical characteristics of the measured variables
Table 2  Basic statistical characteristics of the individual subjects

<table>
<thead>
<tr>
<th>Variable</th>
<th>1, m = 94 kg</th>
<th>2, m = 97 kg</th>
<th>3, m = 85 kg</th>
<th>4, m = 86 kg</th>
<th>5, m = 90 kg</th>
<th>6, m = 81 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>$t_{IN}$ (s)</td>
<td>0.484</td>
<td>0.061</td>
<td>0.436</td>
<td>0.132</td>
<td>0.360</td>
<td>0.050</td>
</tr>
<tr>
<td>$t_{STE}$ (s)</td>
<td>0.792</td>
<td>0.167</td>
<td>0.844</td>
<td>0.254</td>
<td>0.878</td>
<td>0.080</td>
</tr>
<tr>
<td>$t_{TOT}$ (s)</td>
<td>1.276</td>
<td>0.181</td>
<td>1.280</td>
<td>0.290</td>
<td>1.238</td>
<td>0.101</td>
</tr>
<tr>
<td>$I_{INI}$</td>
<td>38.2</td>
<td>5.63</td>
<td>34.6</td>
<td>8.93</td>
<td>29.0</td>
<td>3.000</td>
</tr>
<tr>
<td>$I_{STE}$</td>
<td>61.8</td>
<td>5.63</td>
<td>65.4</td>
<td>8.93</td>
<td>71.0</td>
<td>3.000</td>
</tr>
<tr>
<td>$F_M$ (N)</td>
<td>2387</td>
<td>397.0</td>
<td>1897</td>
<td>647.6</td>
<td>2483</td>
<td>422.6</td>
</tr>
<tr>
<td>$F_1$ (N/s)</td>
<td>721</td>
<td>342.2</td>
<td>529</td>
<td>359.0</td>
<td>743</td>
<td>254.6</td>
</tr>
<tr>
<td>$F_A$ (N)</td>
<td>1704</td>
<td>250.6</td>
<td>1471</td>
<td>384.5</td>
<td>1595</td>
<td>243.0</td>
</tr>
</tbody>
</table>

for the three subjects who were ski racers and longest for the three ski instructors. However, the values of force variables, which appeared to be mainly dependent on the weight of individuals, exhibited wide variability.

Discussion

The recorded curve profiles of $F_Z(t)$ acting on individual lower extremities and the resultant curve of their sum were similar to those found in numerous previous studies (Müller et al., 1998; Müller & Schwameder, 2003; Nachbauer & Rauch, 1991, Raschner et al., 1999). Characteristic oscillations at 3–5 Hz evident in the curves were mainly caused by inhomogeneity of the skiing surface (Vaverka, 2007). The described method of kinetic analysis is based on the resultant ground reaction force. The criterion used to divide the turn into its INI and STE phases is the magnitude of the component of the gravity force acting on the skier body and his/her equipment perpendicular to the slope surface. Kinetic analysis of a ski turn demands knowledge of the combined weight of the skier and his/her equipment, plus information on the inclination angle of the slope. Therefore, the method is relatively simple and the use of elementary mathematic operations (e.g., using MATLAB) rapidly provides an exact description of a ski turn. The principle of this method involves determining the time intervals when the $F_Z(t)$ curve passes through the defined criterion, determination of the maximum force, and the integral of this function during the STE phase. The average force ($F_A$) calculated from the force impulse and the duration of the STE phase eliminates errors when determining the force magnitude due to oscillations in the analyzed $F_Z(t)$.

Comparing the results between individual ski runs facilitated the sensitive differentiation of evaluated data from individuals (Table 2). For example, a simple comparison of the turn duration between the three racers and the three ski instructors reveals the validity of the evaluated data because it unambiguously shows the expected differences in speed between these two groups. Data on the time courses of turn phases and the magnitudes of acting forces are influenced by the conditions of a particular ski run, such as the speed, turn radius, and slope inclination. However, the percentage durations of the individual turn phases relative to the total duration of the turn are more general aspect and hence can be compared for different types of turn.

The two methods commonly used to analyze skier motion (kinematic analysis and dynamometrical measurements of ground reaction forces) (Müller et al., 1998; Raschner et al., 1999) have both advantages and disadvantages depending on the provided information and actual data acquired. Kinematic analysis provides quantitative information on the positions of the skier’s body and the skis in space and expresses movement using several kinematic characteristics: trajectory, angle, velocity, angular velocity, acceleration, and angular acceleration. A descriptive verbal characterization based on quantitative kinematic data are very useful for practice methodology and improving the technique of racers. One important advantage of this approach is that it is possible to analyze skier movement in real conditions, which is particularly important for racers. However, considerable disadvantages of this method are the large demands on the techniques required to record the ski run (e.g., three-dimensional orientation of cameras), the relatively long time required to evaluate visual records, and above all the lack of information on the acting forces.

Dynamometric recording of acting forces provides information on the magnitude of the ground reaction forces acting on individual extremities, and on the resultant actions. It provides the force conditions of the interaction between the skier and the terrain, and thereby indirectly the forces that manifest in the individual. The main advantage of this method is the ability to quantitatively assess the magnitude and time course of the acting ground reaction forces. The available technology makes the recording and evaluation of acting forces simpler than in kinematic analysis. A disadvantage of dynamometry is the necessity to use the same skis and the same system
to measure acting ground reaction forces for different persons, which makes the analysis of racing motion in real conditions impossible.

Differences in the definition of particular phases of the skier’s turn originate from the criterion used. Dividing the turn into particular phases on the basis of kinematic analysis is reliant on subjective decisions of authors and the obtained kinematic data. On the other hand, the method of kinetic analysis of a skier’s turn presented in our paper originates from general physical theory and provides qualitatively new information about particular phases of the turn. Therefore, our method clearly differs from the classic approaches used by other authors to divide ski turns into specific phases.

Published works in the field of dynamometric measurement of acting ground reaction forces, and combined kinematic analysis and dynamometry, have tended to describe the force curves verbally and have not used a standardized method of evaluation. In contrast to the different reported opinions about the particular ski turn phases resulting from subjective descriptions of movement skier actions, a fundamental element of the novel method presented here is the exact definition of turn phases based on physical theory. The use of standardized turn phases is crucial to their accurate time identification and for quantifying the magnitudes and force impulses of the acting forces. This methodology makes it possible to describe ski turns using accurately measured biomechanical variables, and hence will be useful for addressing various research questions associated with ski turns.

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References


