Kinematic Characteristics of the Ski Jump Inrun: A 10-Year Longitudinal Study

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The athlete’s inrun position affects the outcome for take-off in ski jumping. The purpose of this study was to examine the kinematic parameters between skiers’ adjacent body segments during their first straight path of the inrun. Elite ski jumpers participated in the study at the World Cup events in Innsbruck, Austria, during the years 1992 through 2001. A video image was taken at a right angle to the tracks of the K-110 (meter) jumping hill. Kinematic data were collected from the lower extremities and trunk of the athletes. Findings indicated that jumpers had diminished ankle and knee joint angles and increased trunk and hip angles over the 10 years. In recent years, the best athletes achieved a further length of their jumps, while they experienced slower inrun average velocity. These results are perhaps explained by several possible contributing factors, such as new technique of the jumper’s body kinematics, advancements in equipment technology, and somatotype of the jumpers.

Keywords: biomechanics, performance, winter sports

As the sport of ski jumping evolves, the physical demands on athletes increase. The inrun body position, as one of the basic positions in ski jumping, becomes a focus of attention in research because reaching the optimal inrun velocity and body posture are the key factors for maximal jump length (Dželalija et al., 2003; Vaverka, 1987; Baumann, 1979; Komi et al., 1974). The objective of the ski jumper in this first straight phase of the jump is to assume a position that results in optimum take-off execution without losing velocity. To understand ski jumpers’ inrun positions, we need to distinguish how external influences (e.g., equipment and skiing conditions) relate to the movement execution of ski jumpers.

Virmavirta and Komi (1991) investigated the electromyography (EMG) activities during the inrun. In the straight path of the inrun the EMG was relatively low, associated with limited knee extensor activation. The EMG was relatively higher in the curve path as a result of jumpers’ increased muscle activities of the vastus lateralis and medialis to compensate for the increased centrifugal force due to the curvature of the inrun under actual hill jumping conditions. Another EMG study included the analysis of plantar pressures and found a pressure increase under the toes during the inrun curve that might help jumpers maintain better balance at take-off. In addition, the results showed that the differences in plantar pressure and EMGs between the jumping hills (K-35 m, K-65 m, and K-90 m) were smaller than expected for both jumpers (Virmavirta, 2000; Virmavirta et al., 2001a).

Vaverka and Zháněl (1989) found that the body kinematic parameters during the straight inrun path differed from the values on the curve path. Specifically, the ankle and the knee angle increased, and the body center of mass (CoM) shifted backward on the curve inrun path.

Recent studies have used kinematics to focus on the inrun phase through the use of modeling and numerical simulation (Mielnik & Saetran, 2000; Ettema et al., 2005). From a kinematics perspective, the basic forces applied on the ski jumper as he or she skis the first straight path are weight (W), kinetic friction ($F_f$), normal force ($R_n$), drag force ($F_d$), and lift force ($F_l$) (Figure 1). It is at this point of the inrun that the jumper must do several tasks (i.e., keep his balance and prepare for take-off) to reach the maximal take-off velocity.

A net force acting on the ski jumper can be calculated by comparing the applied forces in the following equation:

$$m \cdot a = W \cdot \sin \theta - F_f - F_d =$$

$$m \cdot g \cdot \sin \theta - m \cdot \mu \left( \frac{v^2}{r} + g \cdot \cos \theta \right)$$

$$= \frac{1}{2} \cdot c_d \cdot \rho \cdot v^2 \cdot A_d$$

(1)
where \( m, a, \) and \( v = \) mass, acceleration, and velocity of the jumper and his equipment; \( \theta = \) angle of the slope, \( \mu = \) coefficient of snow friction, \( r = \) radius of the curve path, \( c_d = \) drag coefficient, \( \rho = \) air density, and \( A_d = \) surface area perpendicular to the direction of motion, \( g = 9.81 \text{ m/s}^2. \)

For the straight path radius \( r \to \infty, \) then \( v^2/r \to 0. \)

The jumper’s acceleration is derived from the equation

\[
a = \frac{dv}{dt} = \frac{d(v^2)}{2 \cdot ds}
\]

where \( s \) is distance, and then

\[
\frac{d(v^2)}{ds} = 2 \cdot g \cdot (\sin \theta - \mu \cdot \cos \theta) - c_d \cdot \rho \cdot \frac{v^2}{m} \cdot A_d
\]

And solving the first-class differential equation (Mielnik & Saetran, 2000),

\[
v = \pm \sqrt{g \cdot (\sin \theta - \mu \cdot \cos \theta) \cdot \left(1 - e^{-c_d \cdot A_d \cdot \frac{\rho}{2 \cdot m}}\right)}
\]

According to Equation (4), the jumper achieves the maximal inrun velocity if the mass \((m)\) is increased, the coefficient of friction \((\mu)\) is decreased, and the magnitudes of \( c_d \) and \( A_d \) (depending on the body position with respect to drag) are reduced. These conclusions are also logically derived from observing jumpers’ body movements during inrun execution. On the other hand, these theoretical conclusions apply to the inrun but may be counterproductive for a flight phase of the jump as the sport has assumed that the less mass a ski jumper has the better chances of a successful jump (Vaverka, 1987).

During the observed 10 years, we have seen changes in the jump technique in all basic phases. It was hypothesized that we would see differences in the position of skiers’ individual body segments as they ski during the inrun phase. The purpose of this 10-year study was to establish how changes of external conditions influence changes in certain segments of athletes’ bodies during their inrun.

**Methods**

Elite male ski jumpers \((n = 656)\) participated at the FIS World Cup events in Innsbruck, Austria, during the years 1992 to 2001. From this population, the 15 best ski jumpers \((n = 15)\) were selected (based on the longest jump achieved in each meet).

Two-dimensional video image data were recorded using a stationary camera (either a Grundig S-VHS 180 [1992–1999] or a Sony DCR-TRV 900 [2000–2001]) with sampling frequency of 50 Hz. The video data were recorded from the same place at right angles to the ski track of the K-110-m hill along the initial straight path of the inrun about 18 m from the platform edge (Figure 2). The start position was chosen by competition judges based on weather condition, ski friction, and changes in gear and jumping technique. Wind velocity and direction were measured according to the FIS guidelines, and weather conditions for each year are described in Table 1. Also the devices for the measurement of tangential component of inrun velocity were placed according to the FIS rules; that is, the measured distance was 8 m, the second photocell beam was located 10 m before the edge of the takeoff, and the photocell beam was 0.2 m above the snow profile (International Ski Federation, 2004).

A seven-link bilateral model was created based on 10 joint points with the CoM defined by Dempster (1955). The model included the following segments: foot, shank, thigh, trunk, head and neck, upper arm, and forearm (wrist included). Kinematic data were collected from the ankle, knee, hip, trunk, and the body CoM in the sagittal plane, and data analysis was performed using software written in Pascal (Vaverka et al., 1994).
Table 1  Data from the World Cup meets in ski jumping at Innsbruck, Austria, 1992 to 2001

<table>
<thead>
<tr>
<th>Year</th>
<th>Round</th>
<th>Snow temperature (°C)</th>
<th>Air temperature (°C)</th>
<th>Wind velocity (m s⁻¹)</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>T1</td>
<td>–8</td>
<td>–1</td>
<td>0–2</td>
<td>Chance of rain</td>
</tr>
<tr>
<td>1993</td>
<td>T1</td>
<td>–13</td>
<td>–10</td>
<td>0–1.5</td>
<td>Clear</td>
</tr>
<tr>
<td>1994</td>
<td>C1</td>
<td>0</td>
<td>+4</td>
<td>0</td>
<td>Chance of rain</td>
</tr>
<tr>
<td>1995</td>
<td>C1</td>
<td>–3</td>
<td>–3</td>
<td>0–2</td>
<td>Sunny</td>
</tr>
<tr>
<td>1996</td>
<td>Q</td>
<td>–3</td>
<td>–1</td>
<td>0–0.6</td>
<td>Sunny</td>
</tr>
<tr>
<td>1997</td>
<td>T2</td>
<td>–3</td>
<td>–4</td>
<td>0–2.7</td>
<td>Chance of rain</td>
</tr>
<tr>
<td>1998</td>
<td>T1</td>
<td>0</td>
<td>+5</td>
<td>0–1.9</td>
<td>Partly cloudy</td>
</tr>
<tr>
<td>1999</td>
<td>T1</td>
<td>0</td>
<td>+9</td>
<td>0.7–3.1</td>
<td>Partly cloudy</td>
</tr>
<tr>
<td>2000</td>
<td>C1</td>
<td>0</td>
<td>+3</td>
<td>0.1–1.5</td>
<td>Cloudy</td>
</tr>
<tr>
<td>2001</td>
<td>C1</td>
<td>0</td>
<td>+6</td>
<td>0.1–2.3</td>
<td>Cloudy</td>
</tr>
</tbody>
</table>

Note. T = trial round, Q = qualification round, C = competition round.

Figure 2 — Body segmental angles and the camera placement (transverse view). Note. The CoM angle is defined as the angle between the line connecting the body’s CoM and ankle and the tangential component of movement. The hip angle is defined as the angle between the line connecting the hip and ankle and the tangential component of movement.
The length of a recorded sector was 1.4 m, and the image had a resolution of $640 \times 480$ pixels; that is, a shift of the cursor by 1 pixel was equivalent to a magnitude difference of 0.003 m. The accuracy of the body angular values had been quantified in a previous study. The magnitude of the relative error was 0.51%, and the absolute error was 0.22°, respectively (Janura & Vaverka, 1997).

All data collection and analyses were done by one researcher, and the reliability of the collected data were calculated with the interclass correlation coefficient (ICC) in the range from 0.931 to 0.971 (Janura, 1996).

A one-way ANOVA with a Fisher test used for post hoc analysis was performed using STATISTICA (Version 6.0, Stat-Soft, Inc., Tulsa, Oklahoma, USA) for all measured and calculated parameters. $P$-values less than .05 were deemed significant throughout.

### Results

#### Comparison of Inrun Velocity and Length of Jump Over the 10 Years of Competitions

Figure 3 shows that the average inrun velocity was the greatest in 1992 ($p < .01$), and the length of jump was the shortest during the early years (1992–96) of measurement for the best 15 jumpers ($p < .05$). Later, the average velocity was smaller during 1993–95 ($p < .01$) and increased during 1996–99 ($p < .01$) for both groups, and the inrun velocity was smallest at the end of the observed period, that is, the year of 2001 ($p < .01$). The length of jump was, during the measured period, similar with the exception of 1997 and 2000 for the all jumpers. For the best jumpers, the length of jump was higher ($p < .05$) during the second

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**Figure 3** — Graphic representation of the average inrun velocity and length of the jump for all jumpers (A) and the best jumpers (B) across the 10 years of the study.
half of the measured period. From the graphic relationship of the inrun average velocity ($v$) and length of the jump ($s$) (Figure 3), the best 15 ski jumpers jumped further ($p < .01$) with the comparative inrun velocities.

**Comparison of Lower Extremity, Trunk, and CoM Positions Over the 10 Years of Competitions**

During these years the jumpers reduced their ankle ($\phi_a$) and knee ($\phi_k$) joint angles (Figure 4) while their trunk angle ($\phi_t$) increased (Figure 5). Year 1994 was an exception due to the combination of higher temperature, a “classic” base from older snow, and rain, which resulted in the CoM shifted backward ($p < .01$). The graphic comparison between all the competitors and the 15 best jumpers in the inrun position between 1992 and 2001 are illustrated in Figure 6. Figure 7 shows a trend of increasing hip angle ($\phi_h$) from 109.9° to 113.5° in 2001 ($p < .01$); best jumpers from 110.1° to 114.3° ($p < .01$).

**Summary of the Essential Findings**

1. In most recent years, the best ski jumpers achieved the furthest length of jumps with slower average inrun velocity compared with earlier ($p < .01$).
2. In most recent years, the position of the ski jumpers during the inrun phase was characterized with the smaller ankle and knee joint angles ($p < .05$) and larger trunk angle ($p < .05$) for all jumpers. In addition, the hip joint shifted backward with respect to the ankle joint.
3. A change of the trunk angle had a regulatory character, whereas the position of the body CoM had large variability and was influenced by the position of the lower extremity segments.

![Figure 4](image_url) — Graphic representation of the ankle and knee angles for all jumpers (A) and the best jumpers (B) across the 10 years of the study.
Discussion

It can be concluded from our study that the inrun position of the jumper affects the jumping performance. The ski jumpers had smaller ankle and knee joint angles along with a larger trunk angle. In addition, we noted a backward shift of the hip joint with respect to the ankle joint. Changes of the inrun body positions reflect the body positions at the take-off (Virmavirta et al., 2001b). The positional changes of the individual segments influence the activation patterns of specific muscles that coordinate body segments in the execution of take-off (Sasaki et al., 1993). A study by Paradis et al. (2001) found, based on the use of stretch–shorten cycles at take-off, that the lower extremities’ segment positions affected jump performance.

The changes found in the segmental positions of the lower extremities did not adjust the CoM location of the jumper. At the transition from the straight run to the inrun curve, a forward shift of the center of pressure (CoP) under the foot usually occurs, which can create an angular momentum that rotates the body against the direction of movement (Ettema et al., 2005). Therefore, a shift of the CoM backward, which occurred in our study, would cause a loss of balance with a risk of falling. However, the quality of the tracks became enhanced during the second part of the observed period, which led to the improvement of the balance conditions.

Several factors may have influenced the significant statistical differences found in our study, including (1) changes in the athletes’ anthropometric parameters (body mass), (2) changes in the inrun velocity, (3) advances in clothing and gear material, (4) changes in flight technique of the ski jumpers, and (5) improvement in tracks.

Body Mass

One of the major contributing factors to improved ski jumping performance was a decrease in body mass index (BMI). The skiers with lower BMI stayed in the air longer and thus achieved maximal jump lengths. Past research has demonstrated that decreased BMI increases the jump’s length (Müller & DeVaney, 1996; Sudi et al., 2004). Specifically, Müller et al. (2006) observed that since 1970 there has been a decrease of the BMI among world-class ski jumpers by 4 units. The influence of the amount of the muscle mass on a specific body position is important, and the increase of muscle mass limits the range of motion (Vaverka, 1987).
Inrun Velocity
Attaining maximum inrun velocity is one of the athletes’ main objectives. Since the athletes in our study had changes in body kinematics, the air resistance might increase resulting in slower inrun velocity (Virmavirta & Komi, 1993; Virmavirta et al., 2001b). Even with the above-mentioned kinematic changes, the athletes had longer jumps, which were influenced by different flight techniques.

Flight Technique
The jumpers started to use several modifications of the V-style technique during the later part of the study, which likely was associated with changes of lift and drag forces, and which resulted in longer jumps. The changes of the V-style technique in the flight phase caused the changes in kinematic parameters during the inrun and take-off phases (Schmölzer & Müller, 2005; Virmavirta et al., 2001b).

Gear
Furthermore, the inrun position changes observed in the study may have been a result of alterations in the gear and the clothing material, as dictated by the competition rules. Over the 10 years of observations, average ski length increased, which along with aerodynamic affects associated with suit materials and shapes, likely was a contributing factor to increased jump length.

Quality of Tracks
For the duration of the first years of the study, the quality of the tracks was less than optimal in regard to air temperature and snow conditions. However, during the later years, minimal differences occurred in track layout, with more consistent hill preparation across the individual meets due to the advances in technology. Improvement of track quality likely resulted in greater velocity from
a given start position and probably made it somewhat easier for jumpers to hold balanced positioning during the inrun. Throughout the first years of the observed time period, the straighter inrun body position showed that the jumper can react to an imbalance with fast contractions of specific muscles (Vaverka, 1987).

Wind

The influence of the wind on the jump quality has been evaluated using a wind tunnel. Virmavirta et al. (2001b) analyzed the aerodynamics of take-off and found that take-off duration was reduced as the wind exerted greater influence against the jumper’s movement. This change resulted from the wind enhancing the lift by decreasing the magnitude of the resultant force that the jumper must overcome. From a numeric simulation of the inrun position, the magnitude of the lift force was assumed to be 10% of the drag force and that was used as input in the model (Ettema et al., 2005). This ratio changes as velocity and wind direction changes.

Group Composition

The variability and group composition of the jumpers showed that the magnitude of the interclass variability is larger than the intraclass variability. These results are consistent with other studies (Janura, 2004; Schwameder et al., 1997). Sudi et al. (2002) assessed fat components among the ski jumpers from 15 countries. The jumpers from the Northern European countries had higher fat component values in both their trunk and lower extremities than did the jumpers from Eastern Europe.

A limitation of the study should be noted. Our results cannot be generalized to other hills because there is a difference in construction parameters among jumping hills, such as the length of the inrun from the highest starting place to the beginning of the takeoff platform, the length of the takeoff, the gradient of the straight section of the inrun, the gradient of the takeoff, and the radius of the curve from the inrun to the takeoff.

To summarize the above findings, we concluded that the main factors causing differences in the inrun body positions of the jumpers included changes in the jump technique along with the advancements of technology, morphological parameters of the jumpers, and the construction of the inrun tracks during the study. These evolutions of the sport have improved the jumpers’ performance.

References


