

# **Kinematic analysis of the flight phase of the Nordic combined and ski jump on a large hill (HS-134 m) during the 2009 Nordic World Ski Championships**

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The purpose of this study was to assess the execution of the flight phase in the Nordic combined (NC) among three groups of competitors, representing different skill levels, and to compare them with three groups of ski jumpers (SJs). Thirty NC and thirty SJ competitors, who performed ski jumps on an HS-134 m jumping hill, were divided into three subgroups based on jump length execution. Two-dimensional (2-D) kinematic data were collected from the lower extremities, trunks, and skis of the competitors. The SJ group had a smaller lower extremity angle ( $p < 0.05$ ), which results in the larger center of mass anterior movement ( $p < 0.05$ ) in comparison to the NC competitors. The NC competitors achieved jump lengths comparable to those of the SJ competitors by having significantly higher in-run velocities.

*Key words: biomechanics, flight phase, Nordic combined, ski jumping, 2-D videography*

## **1. Introduction**

Ski jumping, from a biomechanical perspective, involves many parameters (e.g., accurate timing and appropriate angular momentum at take-off, advantageous body and equipment configurations during the flight), which make enormous demands on ski jumping competitors. To respond to these demands, athletes have to solve extremely difficult optimization problems within a very short time [1]. The Nordic combined (NC) is even more complicated than the ski jumping (SJ) because its performance depends on two disciplines: SJ and cross-country ski racing, which differ in biomechanical and physiological parameters [2]. There are fewer studies on NC than on SJ, and the scientific literature related to kinematic analyses

of basic jump phases in NC is limited [3]. Although some studies on NC have been published in the NC biomechanical literature [4], others have been published as part of the literature on muscle physiology [5] and lower limb strength [6].

Flight phase execution has an important influence on the length of the jump [7], [8]. At the same time, however, technique errors made by a ski jumper in previous phases (especially the take-off phase) cannot be eliminated through flight-phase techniques [9].

The force acting on a jumper during his flight is the summation of aerodynamic and gravitational forces, calling for overall body torque to be balanced close to zero [10]. The magnitude of the lift and drag forces for an optimal flight position is influenced by the angular momentum at take-off

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[11], and the goals, in the flight phase of a jump, are to achieve an optimal lift-to-drag ratio and to maintain a stable body position [12]. Jump length maximization and flight stability depend on the anthropometrical properties of the athlete and the equipment used [13].

The research contains some comparisons of ski jumpers at different performance levels [8], [9], [14], [15]. Yet, the variability within the levels is so large that some competitors in the middle group may actually belong to a lower- or higher-level group. Thus, it is necessary to focus on the variability within a given performance level.

## 2. Purpose

The purpose of this study was to assess the execution of the flight phase in the NC among three groups of competitors, representing different skill levels, and to compare their performance with that of an SJ group.

## 3. Material and methods

### 3.1. Participants

A total of 48 male NC competitors jumped off the large HS-134-m hill during the 2009 Nordic World Ski Championships in Liberec, Czech Republic. Of the 48 athletes, 30 were selected based on the length of the jump (LJ) and were divided into three groups: (1) elite (E;  $n = 10$ , LJ 121–136 m), (2) mediocre (M;  $n = 10$ , LJ 114–118 m), and (3) poor (P;  $n = 10$ , LJ 101–111 m). In addition, of the 72 male SJs participating on the same jumping hill, 30 were chosen and divided according the same rules into three groups: (1) elite (E;  $n = 10$ , LJ 128.5–130 m), (2) mediocre (M;  $n = 10$ , LJ 115.5–117 m), and (3) poor (P;  $n = 10$ , LJ 97–105.5 m).

### 3.2. Apparatus

Video image data were obtained from two digital video cameras (Sony HDV 1080i, Sony DCR-TRV

900E, Tokyo, Japan, 50 Hz), which were located perpendicular to the sagittal plane of SJs' movements, at a distance of 28 m and 60 m behind the jumping hill edge. Because the conditions on the jumping hill did not facilitate the performance of three-dimensional (3-D) measurement, we opted for a 2-D kinematic analysis in the sagittal plane. The image space was calibrated by a 1-m arm cross-calibration frame placed in the plane of the movement at the beginning and at the end of the observed section. The length of a recorded sector was 7 m, and the image had a resolution of  $640 \times 480$  pixels, i.e., a shift of the cursor by 1 pixel was equivalent to a magnitude difference of 0.011 m. The accuracy of the body angular values had been quantified in a previous study, in which the magnitude of error for the recorded sector of approximately 1.4 m was 0.51%, and the absolute error was 0.22%, respectively [16].

### 3.3. Data analysis

The data were manually digitized by an experienced lab technician. We assumed a symmetrical ski jumper's body position in the sagittal plane. A four-link bilateral model was created based on nine points: tip and tail of the ski, ankle, knee, hip, top of the head, shoulder, elbow, and wrist. The model included the following segments: lower extremity, trunk and head, and skis (figure 1). For the calculation of the ski jumper's center of mass (CoM), data on the relative mass of segments [17] were added to data on the relative mass of the skis and gear.

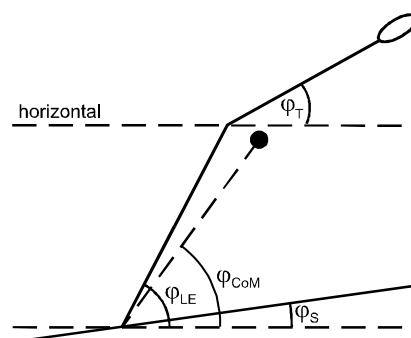


Fig. 1. Measured angular parameters:  $\varphi_T$  – trunk angle to horizontal,  $\varphi_{LE}$  – lower extremity angle to horizontal,  $\varphi_S$  – ski angle to horizontal,  $\varphi_{CoM}$  – angle between CoM and ankle connection and horizontal

The value of the mean joint angular velocity was determined as a ratio of the mean joint angle change to time between the beginning and end of the

observed section. The CoM angle was calculated as the angle of the line passing through the ankle joint and CoM relative to horizontal. The angle parameters were added to the existing parameters of the vertical lowering of the CoM in the observed section (23–33 m).

Two-way ANOVAs (independent variables = discipline and performance level) with a Fisher's post-hoc test were performed (STATISTICA, Version 8.0, Stat-Soft, Inc., Tulsa, USA). The desired power of the study was 0.80 for the differences in the variables. *P*-values less than 0.05 were deemed significant throughout.

## 4. Results

The observed parameters of the flight phase of the NC and SJ are presented in the table. There is no statistically significant difference in the length of jump between the groups. Overall, however, the NC group

exhibited a larger in-run velocity than did the SJ group ( $p < 0.01$ ) at every level of performance.

### 4.1. Observed section 23–33 m behind the jumping hill edge

#### 4.1.1. Comparison of the SJ competitors with different performance levels

The E and M groups had a smaller trunk angle than did the P group ( $p < 0.05$ ) at 23 m behind the jumping hill edge. At 33 m behind the jumping hill edge, the E group, in comparison to the P group, also had a smaller trunk angle ( $p < 0.05$ ). Additionally, in the whole section, the E group, in comparison to the P group, had a smaller lower extremity angle ( $p < 0.01$ ). Additionally, a smaller CoM angle was observed in the E group, as compared to the P group, at the beginning (23 m) ( $p < 0.01$ ) and at the end (33 m) ( $p < 0.05$ ) of the section, as seen in figures 2 and 3.

Table. Parameters of the NC and SJ competitors

Parameters	Nordic combined						Ski jumping					
	E		M		P		E		M		P	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
<i>LJ</i> (m)	126.05	2.18	115.30	0.929	104.05	5.45	125.45	3.00	114.40	1.05	102.05	4.87
<i>v</i> (m·s <sup>-1</sup> )	26.25	0.177	26.11	0.150	26.14	0.118	25.73	0.091	25.68	0.095	25.66	0.096
$\varphi_T$ 23 (°)	11.93	4.01	13.78	3.50	19.28	4.36	16.81	4.36	16.37	4.24	19.93	2.85
$\varphi_T$ 33 (°)	6.69	3.45	8.13	4.43	12.80	4.27	8.88	3.01	10.14	3.40	13.32	4.08
$\omega_T$ (°·s <sup>-1</sup> )	12.95	7.71	13.65	4.67	15.57	9.57	19.36	7.42	15.25	7.13	16.05	8.69
$\varphi_{LE}$ 23 (°)	41.06	3.02	41.21	5.50	42.56	4.15	36.57	5.00	39.54	3.96	43.12	6.03
$\varphi_{LE}$ 33 (°)	35.91	4.38	34.64	3.46	38.31	4.74	30.29	3.23	32.07	3.95	34.18	3.80
$\omega_{LE}$ (°·s <sup>-1</sup> )	12.75	8.18	15.89	9.92	10.21	8.92	15.33	9.01	18.29	6.07	21.73	10.79
$\varphi_S$ 23 (°)	15.32	7.91	15.53	4.34	16.32	6.67	14.78	4.45	11.91	5.32	13.52	2.88
$\varphi_S$ 33 (°)	7.65	2.98	6.33	3.46	11.51	7.30	8.58	3.35	7.20	5.92	8.84	3.53
$\omega_S$ (°·s <sup>-1</sup> )	18.95	18.99	22.24	6.25	11.55	16.85	15.13	5.15	11.52	13.33	11.37	6.47
$\varphi_{CoM}$ 23 (°)	32.85	3.35	32.84	4.84	34.95	3.16	29.76	3.44	31.68	3.99	35.32	4.25
$\varphi_{CoM}$ 33 (°)	27.90	3.49	26.81	3.11	30.82	3.74	23.28	2.85	24.94	4.04	27.46	3.18
$\omega_{CoM}$ (°·s <sup>-1</sup> )	12.22	5.02	14.57	7.98	9.89	9.03	15.83	7.02	16.49	6.64	19.12	7.68
$\Delta CoM$ (m)	3.25	0.12	3.36	0.12	3.33	0.11	2.90	0.13	3.06	0.10	3.05	0.11
$\varphi_T$ 60 (°)	2.90	2.67	2.06	4.97	2.17	2.74	0.79	1.79	-0.12	3.52	3.68	2.45
$\varphi_{LE}$ 60 (°)	27.37	2.93	26.64	2.56	28.15	4.62	20.78	4.32	24.14	3.81	30.04	5.14
$\varphi_S$ 60 (°)	1.13	3.32	1.94	3.57	2.74	3.75	0.81	2.94	0.74	3.81	4.41	2.19
$\varphi_{CoM}$ 60 (°)	20.25	2.89	19.84	2.28	21.08	3.87	14.53	3.27	16.88	4.08	22.55	3.88

Legend:

*LJ* – length of jump, *v* – in-run velocity,  $\varphi_T$  – trunk angle to horizontal,  $\varphi_{LE}$  – lower extremity angle to horizontal,  $\varphi_S$  – ski angle to horizontal,  $\varphi_{CoM}$  – angle between CoM and ankle connection and horizontal,  $\omega_T$  – trunk angular velocity,  $\omega_{LE}$  – lower extremity angular velocity,  $\omega_S$  – ski angular velocity,  $\omega_{CoM}$  – CoM angular velocity,  $\Delta CoM$  – displacement of the CoM in the vertical direction, 23, 33, 60 – distance (in meters) behind the jumping hill edge.

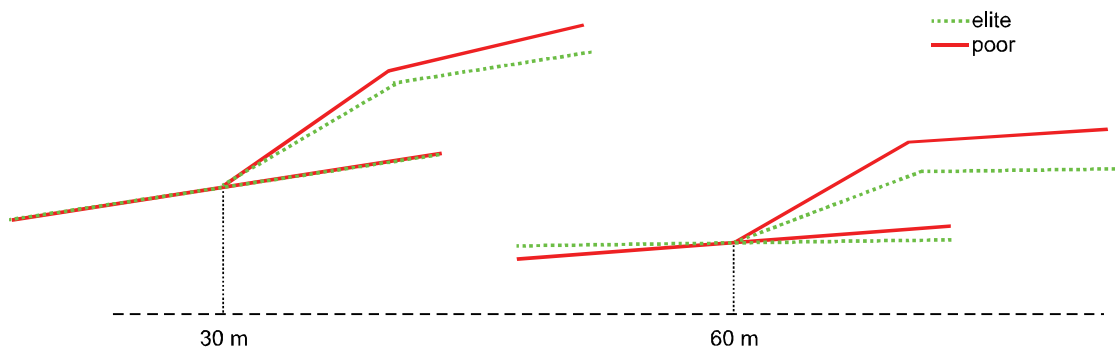


Fig. 2. The graphic comparison of the elite and poor levels' SJs at selected points of the analyzed section (30 m and 60 m behind the jumping hill edge)

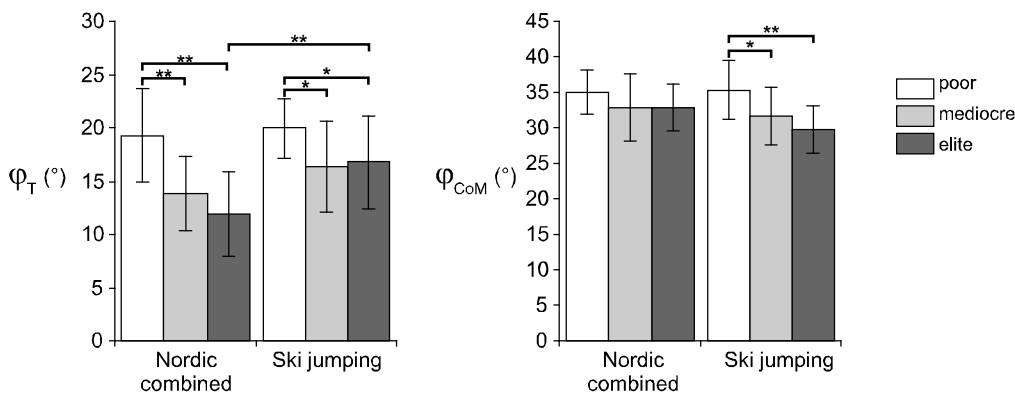


Fig. 3. Comparison of the trunk and CoM angles in NC and SJ groups with different performance levels at 23 m behind the jumping hill edge. \*\*  $p < 0.05$ , \*  $p < 0.01$

#### 4.1.2. Comparison of the NC competitors with different performance levels

The E and M groups had a smaller trunk angle as compared to the P group ( $p < 0.01$ ) in the whole section. At the end of the section (33 m), the P group had a larger ski angle than did the M group ( $p < 0.05$ ). In the whole observed section, the E group had a smaller CoM angle than did the P group ( $p < 0.05$ ), as shown in figures 3 and 4.

#### 4.1.3. Comparison of the NC and SJ competitors

E group: the NC competitors showed a smaller trunk angle at 23 m behind the jumping hill edge ( $p < 0.01$ ). In comparison, the SJ athletes had a smaller lower extremity angle ( $p < 0.05$ ), which may have been a result of the CoM anterior movement 23 m behind the edge ( $p < 0.05$ ), as presented in figure 5.

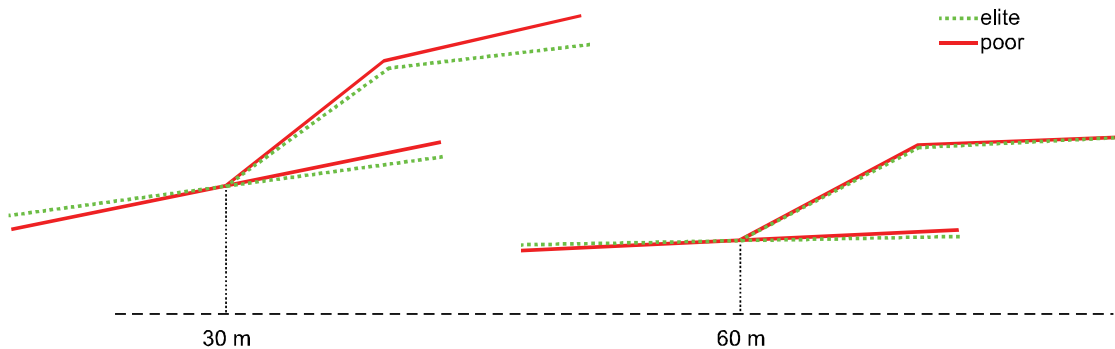


Fig. 4. The graphic comparison of the elite and poor NC competitors at selected points of the analyzed section (30 m and 60 m behind the jumping hill edge)

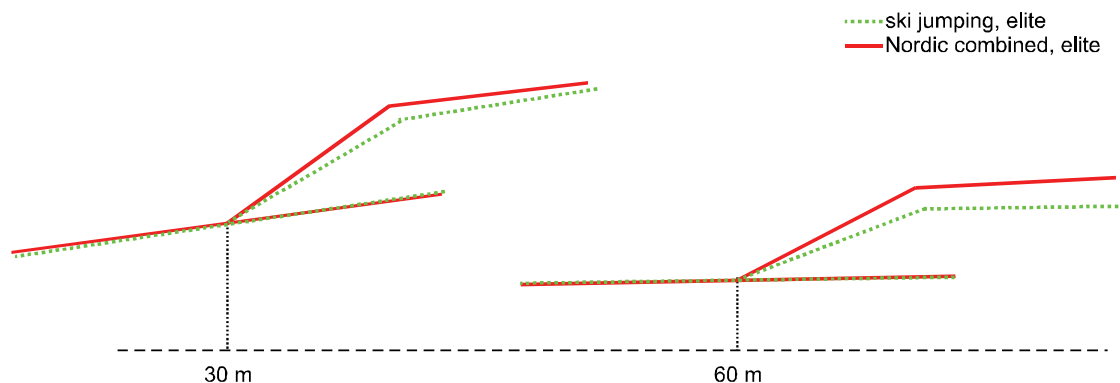


Fig. 5. The graphic comparison of the best NC and SJ competitors at selected points of the analyzed section (30 m and 60 m behind the jumping hill edge)

M group: in comparison to the NC athletes, the SJ group had a smaller range of ski movements ( $4^\circ$  SJ vs.  $9^\circ$  for NC) ( $p < 0.05$ ) as well as a smaller vertical lowering of the CoM in the whole section ( $p < 0.01$ ).

P group: in comparison to the NC group, the SJ competitors had a higher lower extremity angular velocity ( $p < 0.05$ ) and a smaller vertical lowering of the CoM ( $p < 0.01$ ) in the observed section. Additionally, this group demonstrated a smaller lower extremity angle at 33 m behind the jumping hill edge ( $p < 0.05$ ).

## 4.2. Observed section 60 m behind the jumping hill edge

### 4.2.1. Comparison of the SJ competitors with different performance levels

In comparison to the P group, the E and M groups had a smaller trunk angle ( $p < 0.05$ ) and a smaller lower extremity angle ( $p < 0.01$ ). Additionally, in

comparison to the M group, the E group had a smaller lower extremity angle ( $p < 0.05$ ). Figure 2 shows the smaller CoM angle in the E group as compared to the P group ( $p < 0.01$ ), while figure 6 depicts a similar CoM position difference between the E and M groups ( $p < 0.01$ ).

### 4.2.2. Comparison of the NC competitors with different performance levels

There were minimal differences among the NC competitors. Nevertheless, among the groups of competitors with similar performance levels, there was large variability in the parameters of body movement execution.

### 4.2.3. Comparison of the NC and SJ competitors

E group: figures 5 and 6 depict the smaller CoM ( $p < 0.01$ ) and a lower extremity angle ( $p < 0.01$ ) for the SJ athletes as compared to the NC competitors.

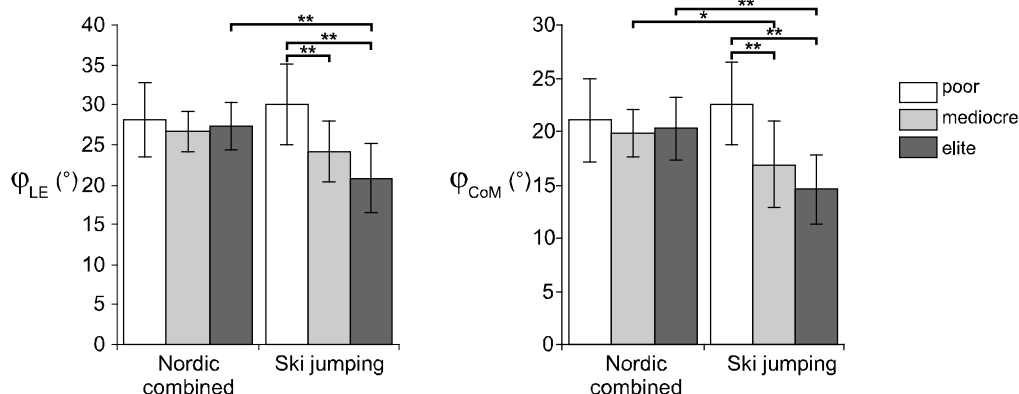


Fig. 6. Comparison of the lower extremity and CoM angles in NC and SJ groups with different performance level at 60 m behind the jumping hill edge.

\*\*  $p < 0.05$ , \*  $p < 0.01$

M group: the SJ group exhibited a larger trunk angle ( $p < 0.05$ ) than did the NC competitors.

## 5. Discussion

According to SCHMÖLZER and MÜLLER [13], the competitor chooses a strategy for the body position of the flight that will result in the maximum jump length under the given conditions (e.g., size and shape of a ramp, weather situation, gear, equipment, somatotype of a jumper). This optimal body position, however, varies according to the athlete.

Previous investigations of elite ski jumping revealed a reduction of the angle between the ski jumper's body axis and horizontal during the middle or the second part of the flight phase, resulting in large jump distances. This reduction in angle shifts the jumper's CoM forward, thereby increasing forward angular momentum, enabling the body to assume the optimal flight position. This "more forward" body position is associated with certain aerodynamics that results in a maximum jump distance [7], [15], [18]. More specifically, Schwameder and Müller claimed that a long jumping distance could be obtained by the optimal combination of high vertical take-off velocity, large rotational impulse at take-off, and a small angle between the body and skis 20 m after take-off [19]. VIRMAVIRTA et al. [8] found a strong relationship ( $r = 0.71$ ) between the length of the jump and a decreased angle between the body position and the skis at a distance of approximately 40 m behind the edge of the hill. Similar to the results of previous research, the elite SJ competitors in our study shifted the hip anteriorly (smaller lower extremity angle) during the flight phase, which was supported by the CoM anterior shift. Elite SJs achieve stable flight positions within 0.5 s (corresponding roughly to 13 m) after take-off. This ideal body position is characterized by an optimal ratio between the aerodynamic forces of drag and lift, a ratio that is necessary for a maximum jump length. The magnitude of the aerodynamic forces is influenced by both the body position assumed by the competitor and the jumper's gear [8].

SJ competitors, compared to NC competitors, employed the advantageous "more forward" body position to achieve maximum jump distances, while NC competitors attained higher in-run velocities to achieve comparable maximum jump distances. A significant correlation between length of the jump, in-run velocity ( $r = 0.63$ ), and hip joint angular velocity ( $r = 0.65$ ) for the best SJ athletes was found in the final round of

the ski jumping competition at the 2006 Olympic Games in Torino [20].

The present study found large variability in the measured parameters within the groups of competitors with similar jump lengths, which may be attributed to the different techniques used during specific phases of the ski jump as well as to different somatic parameters. Previously, JANURA, SVOBODA, and UHLÁŘ [21] demonstrated that the differences among the angular values in five competitors with similar jump lengths are greater than  $10^\circ$ . Large individual variability was also determined by the kinematic analysis at the beginning of the flight and during the flight phases at the 2002 Olympics in Salt Lake City [8], [13]. Other conditions that may cause large variability include environmental influences on jump distance (e.g., random character of air flow turbulence around a ski jumper [22] and wind velocity [23]).

## 6. Limitations and further research

There were several limitations to the study. In practice, we do not encounter championships (competition rounds) with constant external conditions. The wind factor varied from  $0.1\text{--}2.7\text{ m}\cdot\text{s}^{-1}$  (NC) to  $0.4\text{--}3.0\text{ m}\cdot\text{s}^{-1}$  (SJ); however, a comparison of the long-term performance levels of the jumpers and their classification in performance groups shows that the impact of wind was insignificant.

Further research should be based on the set of all measured kinematic parameters together with the internal preconditions of the ski jumpers, e.g., various anthropometric segment parameters and movement abilities, as a means to determine how these preconditions affect performance.

## 7. Concluding remarks

- NC competitors achieved jump lengths comparable to those of the SJ competitors by having significantly higher in-run velocities.
- SJ competitors take a better aerodynamic position in the observed sections than did the NC competitors, who encountered smaller air resistance.
- In the NC group, there were smaller differences among the different levels of competitors with increasing distance behind the jumping hill edge.

- There was large variability in the measured parameters among the competitors at similar performance levels.

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