THE RELATIONSHIP BETWEEN SELECTED KINEMATIC PARAMETERS AND LENGTH OF JUMPS OF THE SKI-FLYING COMPETITION

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Original scientific paper
UDC 796.925:577.3:531.1

Abstract:

The objective of this study was to analyse selected kinematic parameters (time of flying, in-run velocity, take-off velocity, out-run velocity, height of flying at 17 m, height of flying at 75 m, height of flying at 120 m, aerodynamic index at 17 m, aerodynamic index at 75 m, aerodynamic index at 120 m) of the best world-class ski jumpers participating in the two final individual competitions (Friday and Sunday) of the Ski-Flying World Cup at Planica, Slovenia in 2009 (HS 215 m). All jumps were recorded with three video cameras operating at 50 fps, following the jumpers at the early flight phase (17 m from the take-off edge) and in the middle phase of flying (75 m and 120 m from the take-off edge). The ski jumpers were divided into three statistically significantly differentiated quality groups according to their jump lengths in all three rounds ($F_{prob.}$=.01). By means of correlation analysis and single-factor analysis of variance, a smaller number of statistically significant correlations between the defined kinematic variables and the jump length were determined. The differences in the vertical height of flying confirmed a tendency towards positive correlations between this variable and the jump length (r_{min}=.42, r_{max}=.79). The group of the best ski jumpers demonstrated a statistically significant higher vertical height of flying curve in all the three competitive rounds at the points of 75 m ($F_{prob.}$ were between .00 and .08) and 120 m ($F_{prob.}$=.01). The best group of ski jumpers had better aerodynamic positions in the flight phase, especially at the point of 75 m (Sunday, the first round, r =-.73; p =.00) and 120 m (Sunday competition in both rounds, $F_{prob.}$=.01).

Key words: *ski jumps, kinematic flight analysis, Final World Cup Competition 2009, Planica HS 215 m*

Introduction

The competition in the finals of the 2009 World Cup in Ski Flight was selected to investigate the kinematic factors of the techniques used by ski jumpers on the ski flying jumping hill in Planica (HS 215 m). Jumps over 240 m can be realized on this hill; the flying time can be over 7 seconds; the flying velocity can be between 100 km/h and 115 km/h. The variability of length of the jumps on the biggest jumping hill is always much bigger than on normal jumping hills. This is an opportunity to discover some important differences between the best and the less successful ski jumpers with regard to the chosen kinematic parameters of the ski jumping technique. The variability of length of the jumps is represented by differences in the flying curve. The differences in the flying curves are significant on the bigger jumping hills. The kinematic characteristics of the flying curve are consequences of many kinetic factors of the inertial force environment (Vaverka, 1987). For experts and researchers of ski jumping, analysis of the top-level performers' ski-jumping technique is the most frequently used solution in the process of finding optimal technique allowing the ski jumpers to accomplish their best competitive performance. Some of these research studies were more focused on the study of the in-run, push-off and early flight phase techniques (Virmavirta & Komi, 1994; Arndt, Brügemann, Virmavirta, & Komi, 1995; Komi & Virmavirta, 1997; Vaverka, Janura, Elfmark, & Salinger, 1997; Jošt, Čoh, Pustovrh, & Ulaga, 1999; Sasaki, Tsunoda, & Hoshino, 2001; Virmavirta, Kiveskas, & Komi, 2001; Joo-Ho Song, Young-Jin Moon, & Young-Hoo Kwon, 2004; Ettema, Braten, & Bobbert, 2005). Some research studies were more focused on the study of the flight technique (Watanabe & Watanabe, 1993; Jošt, 1994; Hiroshi, Shunsuke, Tadaharu, Hirotoshi, & Kazutoshi, 1995; Jošt, Kugovnik, Strojnik, & Colja, 1997; Jošt, Vaverka, Kugovnik, & Čoh, 1998; Schmölzer & Müller, 2002; Seo, Murakami, & Yishida, 2004a; Seo, Watanabe, & Murakami, 2004b; Schmölzer, & Müller, 2005; Virmavirta, Isolehto, Komi, Brüggemann, Müller, & Schwameder, 2005).

The first goal of the current study was to analyse the relation between in-run and take-off velocity, and the length of flying. The hypothesis was set that the group of best ski jumpers would have a significantly higher in-run velocity than the group of less successful ones. The in-run velocity and take-off velocity influence directly both the horizontal and vertical velocity in the first part of the flight. Performance of a ski jumper, from the aerodynamic factor aspect, first depends on the optimization of the push-off factors in the take--off phase (Virmavirta & Komi, 1994; Komi & Virmavirta, 1997). This means that take-off factors (vertical push-off acceleration, rotation, accuracy of the push-off and the activity of the arms) are aerodynamic efficiency causal factors during the take-off phase (Vaverka, et al., 1997). In the first part of the flying phase, the ski jumper has to assume the optimal aerodynamic position for flying. This will maximize the horizontal velocity and minimize the vertical velocity of flying. From this perspective, it could be expected that the best group of ski jumpers would have a higher flying curve than the group of less successful ones and a better aerodynamic position after the take-off. The flight phase represents a constituent part of the ski jumping technique, which significantly determines the length of the ski jump (Sasaki, et al., 2001; Schmölzer & Müller, 2002, 2005; Seo, et al., 2004). Further, the optimal technique activity of the ski jumper in the flight phase is extremely important. The first parameter that determines the ski-flying technique is the height of the flying curve. The group of least successful ski jumpers has a lower height of flying curve than the best group. The second parameter of the flying technique is the optimal aerodynamic position. The best ski jumpers are supposed to have a better aerodynamic position than the less successful ones. At the beginning of flying, the jumper has to solve two independent tasks of special ski jumping technique. The first one is to reach the optimal height of flying and the second one is to assume and maintain the optimal aerodynamic position (Schmolzer & Müller, 2005; Arndt, et al., 1995; Jošt, et al., 1998; Jošt, et al., 1999; Virmavirta, et.al., 2005). The combination of both parameters is crucial to the best ski jumping technique (Virmavirta, et al., 2005). The height of flying in the beginning of the flight first depends on the take-off force impulse on the take--off table (Virmavirta & Komi, 1994). One part of this take-off force is needed to reach the optimal aerodynamic position and one part to attain the higher curve of flying in the first part of flying. From the aerodynamic aspect of the ski jumping flying technique, the optimal aerodynamic forces (drag and lift force) must be present during the flight phase (Sasaki, et al., 2001). The maximization of lift force has a positive effect on minimizing the negative effect of drag force. In previous research, the most significant correlation with the length of the jump was found in the angle between the body and skis, and the ski angle of attack at the end of the first phase of the flight (Jošt, et al., 1998; Virmavirta, et al., 2004). Drag force, acting negatively in the horizontal plane of flying, has to be minimal throughout the flight phase. For this reason, a special aerodynamic index was developed as the vertical distance between the highest point on the body ski jumpers and the to-the-nearest point of the skis. This index would be in a significant negative correlation with the length of the jump. The best group of ski jumpers should have minimal values, and the below-average group of ski jumpers should have maximal values of the aerodynamic index. One of the goals of this research was to discover the correlation, if any, between the length of the jumps and the out-run velocity measured at the space distances from 245 m to 255 m. Namely, it could be hypothetically expected that the least successful group of ski jumpers had a higher out--run velocity than the best group.

Methods

In this research, the ski jumpers participating in three competitive rounds of the 2009 World Cup in Ski Flights at Planica (HS 215 m) were analysed. On the first day (Friday, 20th March, 2009), 40 jumpers competed in only one round (30 jumpers were analysed). In the second competition day (Sunday, 22nd March, 2009), 34 jumpers competed in the first and 30 jumpers in the final round. The ski jumpers were divided into three quality groups (Best, Average, Below Average) according to the jump length in a particular round. Values of the variables (length of the jumps in metres); time of flying in seconds; in-run velocity expressed in km/h, measured according to the FIS rules at a distance of 8 m, that is, 10–18 m before the take-off bridge; take-off velocity in km/h, measured for the last 10 m on the take-off table; out-run velocity in km/h, measured at the distance between the 245th m and 255th m) were obtained from the official records of the Competition Office. The variables of *in-run*, *take-off* and *out-run velocity* were measured with photocells placed .2 m above the snow profile. The kinematic variables *ski-flying technique movement*, *the aerodynamic index of flying* (m) and the *height of the flying curve* (m) were measured by means of a 2-D video analysis. The weather conditions were excellent during recording, with perfect visibility. The recording was carried out with video cameras with a frequency of 50 frames per second. The first camera recorded flying between the 10th and 25th m, the second camera recorded flying between the 60th and 80th m, and the third camera recorded flying between the 110thand 130th m. Digitalization of the selected frames at the 17th m, 75th m and 120th m was carried out manually. The flight position of individual athletes was recorded at an average height level of the flying curve. Distances between the ski jumper and cameras depended on the given terrain (between 12.5 m and 80 m). For the calibration of the space dimensions at a chosen point of flying, a specially made cross-shaped marker was used. In Figure 1, the method of space calibration at the point 120 m after the take-off bridge is presented.

The significance of the correlation between the variable *length of the jump* and the measured variables was established by using Pearson correlation coefficient (r) for all the subjects in each competitive round. The statistical data were computed for each group separately and reported as means and standard deviations (M, SD). To establish statistical significance of the differences between the groups, a one-way single-factor analysis of variance (ANOVA) was used. The criterion of statistical significance was accepted with a 5% two-sided alpha error in both statistical methods.

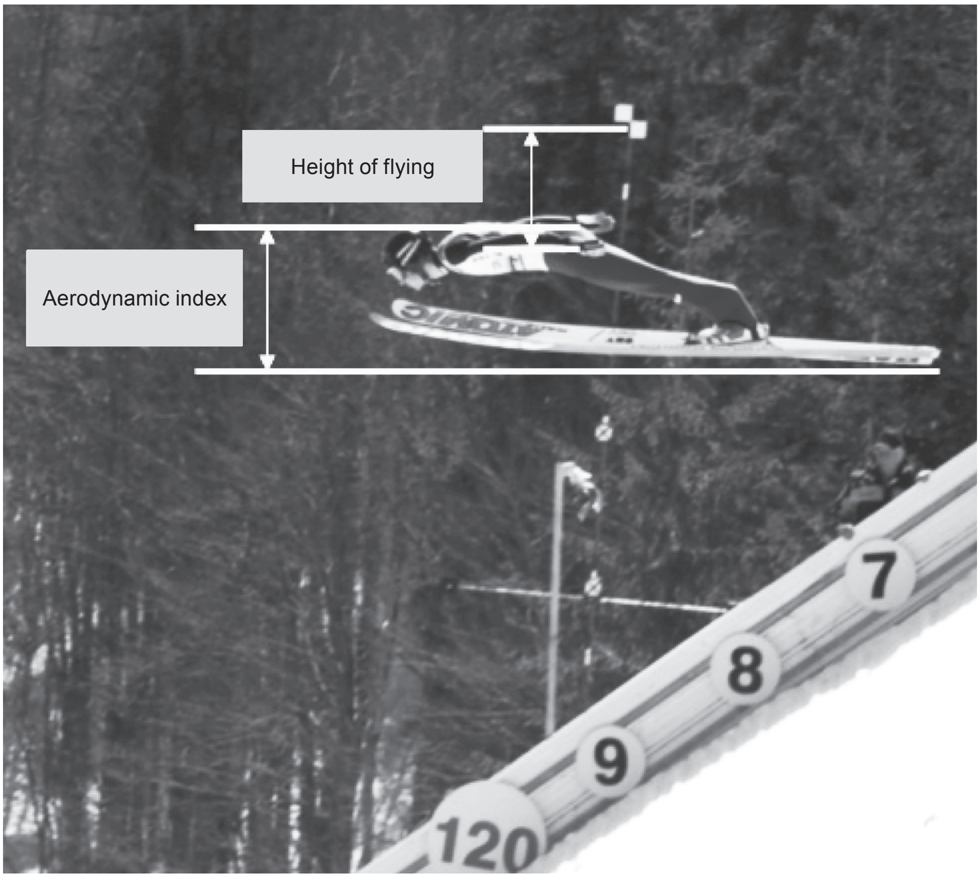

Figure 1. Calibration of the space during a flying phase with the specially cross-measured procedure for taking the data of the variables height of flying *and* aerodynamic index at 120 m.

The 2D model of a jumper's body and skis consisted of a three-segment model with three reference points. The first point on the body, the *trochanter major* point, was used to measure the variable *height of flying* (vertical distance between the snow profile of the jumping hill and the body point *trochanter major*). The second point was determined as the top of the head or *the highest point of the body during the flying phase* in the chosen reference space point. The third point was determined as the nearest vertical point of the ski position. The last two points were used to measure the variable *aerodynamic index* (see Figure 1). The aerodynamic index is the maximum vertical distance between the highest point of the ski jumper's body and to the ground nearest point on the skis. The minimal values of that index indicate a better aerodynamic efficiency of flying.

Results

The differences between the defined quality groups of ski jumpers in the variables of the *jump length* and the *time of flying* were statistically significant ($F_{prob.}$=.01). The maximal differences (45.7 m) existed in the first round of the second competition on Sunday (Table 1).

In Table 2 the statistical results of the in-run, take-off and out-run velocity are shown.

The correlation coefficients between the *length of the jumps* and variables *height of flying at the point of 75 m and 120 m* were statistically significant (Table 3).

Table 1. Analysis of variance for the dependent variables: length of the jump (m) and time of flying (s)

Name of the group	BEST			AVERAGE			BELOW AVERAGE			$F_{prob.}$	
Competitive rounds	n	M (m)	SD (m)	n	M (m)	SD (m)	n	M (m)	SD (m)		
Length of the jump (m)											
Friday 1st round	6	199.7	2.7	11	187.5	5.0	23	164.3	15.6	**.00****	
Sunday 1st round	11	208.2	9.6	12	187.0	4.7	11	162.5	24.5	**.00****	
Sunday 2nd round	14	205.6	7.0	11	189.4	5.1	5	165.2	18.6	**.00****	
Time of flying (s)											r
Friday 1st round	6	6.45	.11	11	6.15	.19	23	5.48	.58	**.00***	.96**
Sunday 1st round	11	6.99	.32	12	6.36	.16	11	5.62	.76	**.00***	.98**
Sunday 2nd round	14	6.91	.27	11	6.32	.11	5	5.65	.64	**.00***	.95**

Table 2. Results of analysis of variance and correlation of the independent variables of velocity

Name of the group	BEST			AVERAGE			BELOW AVERAGE			$F_{prob.}$	r
Competitive rounds	n	M (m)	SD (m)	n	M (m)	SD (m)	n	M (m)	SD (m)		
In-run velocity according to FIS (km/h)											
Friday 1st round	6	103.8	.45	11	103.6	.77	23	103.6	.42	.70	.01
Sunday 1st round	11	101.1	.47	12	100.9	.47	11	101.0	.73	.70	.27
Sunday 2nd round	14	101.6	.52	11	101.8	.46	5	101.2	.54	.14	**.31***
In-run velocity on the take-off table (km/h)											
Friday 1st round	6	103.2	.55	11	103.0	.58	23	103.0	.56	.86	-.06
Sunday 1st round	11	100.5	.53	12	100.3	.48	11	100.1	.67	.41	**.34***
Sunday 2nd round	14	101.0	.52	11	101.0	.55	5	101.0	.43	.98	.15
Out-run velocity (km/h)											
Friday 1st round	6	116.9	1.52	11	114.9	1.90	23	116.9	3.40	.16	-.35*
Sunday 1st round	11	109.1	2.44	12	109.4	3.13	11	109.7	2.89	.88	.03
Sunday 2nd round	14	108.8	3.43	11	110.0	2.43	5	109.8	2.37	.54	-.28

Table 3. Results of analysis of variance and correlation of dependent variables: height of flying at different points of jumping hill

Name of the group	BEST			AVERAGE			BELOW AVERAGE			$F_{prob.}$	r
Competitive rounds	n	M (m)	SD (m)	n	M (m)	SD (m)	n	M (m)	SD (m)		
Height of flying 17m after the take-off edge (m)											
Friday 1st round	6	3.42	.08	11	3.34	.09	23	3.37	.09	.18	.07
Sunday 1st round	11	3.42	.09	12	3.37	.11	11	3.43	.07	.41	-.05
Sunday 2nd round	14	3.36	.09	11	3.33	.14	5	3.24	.08	.17	.23
Height of flying 70m after the take-off edge (m)											
Friday 1st round	6	3.59	.34	11	3.28	.52	23	3.06	.44	**.04***	**.59****
Sunday 1st round	11	3.54	.59	12	2.98	.53	11	3.11	.69	.08	**.42****
Sunday 2nd round	14	3.70	.47	11	2.92	.65	5	2.59	.69	**.00***	**.58****
Height of flying 120m after the take-off edge (m)											
Friday 1st round	6	5.42	.83	11	3.98	.98	23	2.85	1.30	**.00***	**.74****
Sunday 1st round	11	5.34	1.71	12	3.55	.84	11	2.83	1.12	**.00***	**.79****
Sunday 2nd round	14	5.58	1.12	11	3.85	1.27	5	2.22	.79	**.00***	**.73****

Table 4. Results of analysis of variance and correlation of independent variables: index of aerodynamic efficiency of flying at different points of the jumping hill

Name of the group	BEST			AVERAGE			BELOW AVERAGE			$F_{prob.}$	r
Competitive rounds	n	M (m)	SD (m)	n	M (m)	SD (m)	n	M (m)	SD (m)		
Index of aerodynamic efficiency of flying 17 m after the take-off edge (m)											
Friday 1st round	6	1.11	.12	11	1.21	.08	23	1.24	.16	.16	-.17
Sunday 1st round	11	1.13	.12	12	1.14	.07	11	1.23	.19	.24	-.13
Sunday 2nd round	14	1.15	.12	11	1.11	.11	5	1.21	.21	.43	.03
Index of aerodynamic efficiency of flying 70 m after the take-off edge (m)											
Friday 1st round	6	.49	.08	11	.59	.10	23	.54	.09	.17	.07
Sunday 1st round	11	.50	.05	12	.57	.05	11	.60	.10	**.01***	**-.73****
Sunday 2nd round	14	.52	.07	11	.54	.06	5	.57	.05	.49	-.13
Index of aerodynamic efficiency of flying 120 m after the take-off edge (m)											
Friday 1st round	6	.87	.13	11	.94	.13	23	.94	.18	.66	-.18
Sunday 1st round	11	.70	.17	12	.80	.11	11	.91	.16	**.01***	**-.56****
Sunday 2nd round	14	.64	.10	11	.70	.12	5	.98	.45	**.01***	**-.40****

Legend: n – number of jumpers in selected group, M – arithmetic mean of the group; SD – standard deviation within the group; $F_{prob.}$ – significance of the F-test, r – Pearson correlation coefficient with the variable *length of the jump*, (*) – asterisk denotes statistically significant differences between the quality groups of the ski jumpers (*p<.05; **p<.01).

The variables of the *aerodynamic index* were strongly correlated to the *length of the jumps* in the middle of flying at 120 m at the second Sunday competition (Table 4).

Discussion and conclusions

The variability of the defined quality groups of ski jumpers from the aspect of the jump length and time of flying was large and statistically significant in all three rounds ($F_{prob.}$=.01). The jumping distances were, on average, much longer at the Sunday competition than on Friday when the jumpers performed in poor windy conditions (Table 1). The jumpers needed more jumps on the biggest flying jumping hill to adjust their optimal flying technique, which also encouraged a more competitive performance with greater distances.

Generally, the in-run, take-off and out-run velocities were not significantly correlated to the length of the jumps and did not differentiate among qualitative groups in a statistically significant manner (Table 2). Yet, some significant correlations were established (p=.05), but only for one competitive round. The average in-run velocity was a little higher than the velocity on the take-off table. The out-run velocity was by approximately 6 to 10% higher than the in-run velocity. During the first competition round, the out-run velocity was much higher than the ones in the second and third competition rounds. On Friday afternoon, during the first round, wind conditions were not as good as in the second and third competition rounds on Sunday morning. The out-run velocity was strongly influenced by wind conditions. With good wind conditions, the lift force increased and the flying velocity decreased and, consequently, so did the out-run velocity (Schmölzer & Müller, 2002). According to the findings of this study, the development of a new, bigger flying hill could be easier when considering the flying curve.

The variable *the height of flying* attained generally the minimum value at the 17 m point after the take-off edge in all groups of ski jumpers (Table 3). The group of best ski jumpers had, on average, the biggest values in all rounds. The differences between the best group and the below average group were statistically significant in all three jumps at the points of 75 m and 120 m after the take-off table. This difference had mostly already arisen at the flying point of 70 m. The height of flying at the point of 17 m did not significantly differentiate among three qualitative groups of ski jumpers. The differences in the height of flying between the average value of the best, average and below average group were statistically significant at the 70 m point and especially at the 120 m point in all three competitive rounds. The statistical significance increased up to the distance of 120 m and beyond; this differentiated the best from the below-average ski jumpers to a great extent ($F_{prob.}$=.01).

Sports success of ski jumpers depends especially on the aspect of the aerodynamic position of the system body and ski. Bigger differences were expected in the variable *aerodynamic index of flying*. After the take-off (17 m), there were no differences between the defined groups of ski jumpers (Table 4). The first statistically significant differences occured in the first round after the 75 m point in the Sunday competition. In the middle of flying (at the 120th m), important differences were established between the qualitative groups in the Sunday competition in both rounds ($F_{prob.}$=.01).

The aerodynamic index, which indicates the ability of a ski jumper to assume and maintain the optimal aerodynamic position in the central phase of flying, was a statistically significant factor for differentiating between the groups of ski jumpers at the 70 m point and, especially, at the 120 m after leaving the edge of the take-off platform. The ski jumpers of the best group had a better aerodynamic position in the middle of the flight phase then their rivals. In accordance with findings of previous studies and the theory of the technique of the movement of a ski jumper in the main flight phase (Vaverka, 1987), the jumper must, at each point of the flight, assume such a position that will maximize the horizontal velocity while simultaneously minimizing the vertical velocity of the body's centre of gravity movement.

It could be said that ski jumpers developed a good ski-flying position at each time of flying from the beginning to the end. The best group of ski jumpers was more successful in doing so than the below-average group. In some studies, this position was statistically significant and the most important factor for distinguishing between the best and the below-average groups of ski jumpers (Jošt, et al., 1997; Jošt, et al., 1998; Jošt, et al., 1999; Schmölzer & Müller, 2005; Virmavirta, et al., 2005).

On the basis of the results obtained in this research, the following conclusions can be drawn:

- The variability of the defined quality groups of ski jumpers from the aspects of the jump length and the time of flying was large and statistically significant ($F_{prob.}$=.01).
- The in-run velocity showed a positive trend in the discrimination of quality groups of ski jumpers, especially significantly during the Sunday competition in the second round (r=.31, sig r=.05).
- At the point of 75 m and, especially, of 120 m after the edge of the take-off platform, the best group of ski jumpers had the biggest height of flying. The differences in the *vertical height of flying* confirmed a tendency towards positive correlations between this variable and *the jump length* (r_{min}=.42, r_{max}=.79). The best ski jumpers' group attained a statistically significant bigger vertical height of flying in all three competitive rounds at the points of 75 m ($F_{prob.}$=.01/.05/.10) and 120 m ($F_{prob.}$=.01).
- After the take-off phase, the best group of ski jumpers showed tendencies to reach the optimal aerodynamic position in the flight phase (especially important in the middle of flying).
- The velocity of flying during the total phase of flying increased constantly. The out-run velocity was about 6–10% higher than the in-run velocity.
- The out-run velocity in the shortest jumps was not significantly faster than in the longest jumps. Due to bad weather conditions in the first competition round on Friday, when the starting gate was fairly low, the height of starting gate was increased on Sunday, which also increased out-run velocity. In the Sunday 2nd round, a significant correlation (r=-.35, sig r=.05) was established between the *length of the jump* and *out-run velocity*.

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Submitted: April 28, 2010
Accepted: May 2, 2011

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POVEZANOST IZABRANIH KINEMATIČKIH PARAMETARA I DULJINE SKOKOVA NA NATJECANJU U SKIJAŠKIM LETOVIMA

Cilj je ovoga istraživanja bio analizirati izabrane kinematičke parametre (vrijeme leta, brzinu na skakaonici, brzinu odraza, brzinu leta, visinu leta na 17. metru leta, visinu leta na 75. metru leta, visinu leta na 120. metru leta, aerodinamički indeks na 17. metru leta, aerodinamički indeks na 75. metru leta te aerodinamički indeks na 120. metru leta) najboljih svjetskih skijaša letača koji su sudjelovali na dva finalna natjecanja Svjetskoga kupa u skijaškim letovima (petak i nedjelja) na Planici (visina skakaonice 215 m), Slovenija, 2009. godine. Svi skokovi bilježili su se trima kamerama, 50 slika u sekundi, a letači su bili snimani tijekom početne faze leta (17 metara od odraznoga ruba skakaonice) te u središnjem dijelu skoka (75 metara od odraznoga ruba skakaonice i 120 metara od odraznoga ruba skakaonice). Skijaši su bili podijeljeni u tri statistički značajno različite kvalitetne grupe, određene prema duljinama skokova u sve tri skakačke serije ($F_{prob.}$=0,01). Korelacijskom analizom i univarijatnom analizom varijance utvrđena je statistička značajnost manjega broja korelacija među definiranim kinematičkim varijablama i duljine skoka. Razlike u vertikalnoj visini leta potvrdile su tendenciju prema pozitivnim korelacijama između navedene varijable i duljine skoka (r_{min}=0,42, r_{max}=0,79). Skupina najboljih skijaša letača postigla je i statistički značajno višu vertikalnu visinu krivulje leta u sve tri serije letova u točki 75 metara od odraznoga ruba skakaonice (F_{prob} bila je između 0,00 i 0,08) i u točki 120 metra od odraznoga ruba skakaonice ($F_{prob.}$=0,01). Najbolja grupa skijaša letača imala je bolju aerodinamičku poziciju tijekom faze leta, osobito u točki 75 metara od odraznoga ruba skakaonice (prva serija u nedjelju, r =-0,73; p =0,00) i u točki od 120 metara od odraznoga ruba skakaonice (obje skakačke serije u nedjelju, $F_{prob.}$=0,01).

Ključne riječi: *skijaški skokovi, kinematička analiza leta, finale Svjetskoga kupa u skijaškim letovima 2009, Planica – visina skakaonice 215 metara*