Kinematic Analysis of the Take-Off and Start of the Early Flight Phase on a Large Hill (HS-134 m) during the 2009 Nordic World Ski Championships

by

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The take-off is often considered the most significant and difficult phase of a ski jump. Thus, the purpose of this study was to compare three groups of ski jumpers representing different skill levels during the execution of the take-off and start of the early flight phase in ski jumping. A total of 30 athletes, recruited from competitors performing ski jumps on an HS-134 m jumping hill, were categorized into three groups based on jump-length execution. Two-dimensional (2-D) kinematic data were collected from the lower extremities, trunk, and skis of the ski jumpers. Findings indicated that the ski jumpers with shorter jump length demonstrated significantly smaller in-run velocity ($p < .05$), while the elite and mediocre level ski jumpers exhibited a significantly faster shift of the thigh at the transition from take-off into the early flight of the jump ($p < .05$) than did the low-level ski jumpers. In addition, the centre of body mass (CoM) of the elite group shifted significantly more forward over the skis ($p < .01$) than did that of the other two groups. Finally, inter-individual differences existed among ski jumpers at similar performance levels. The largest coefficients of variation (CVs) were found for the position changes of the trunk and shank behind the jumping hill edge.

Key words: *biomechanics, ski jumping, sport performance, 2-D videography*

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Introduction

Ski jumping belongs to the sports disciplines for which complicated and multiple factors (e.g., explosive take-off strength, suitable somatic parameters for optimal effect of the aerodynamic forces in the flight phase) can optimize performance. In early biomechanical studies, a ski jump was divided into three basic phases: in-run, take-off, and flight (Baumann, 1979; Komi et al., 1974; Vaverka, 1987). With the development of theoretical knowledge and quality of measurement technology, attention also has been paid to the early flight, i.e. the transition between the take-off and flight of the jump.

Although each phase of a ski jump is important for an excellent performance, most research considers the take-off to be the key phase of the ski jump (Schwameder, 2008). The kinematic and kinetic patterns of the take-off of a ski jump have been quantified and analyzed by several authors (Janura et al., 2001; Kaps et al., 1997; Vaverka et al., 1996; Virmavirta, 2000; Virmavirta & Komi, 1989; Virmavirta et al., 2001). During take-off, the competitor produces the largest force within the shortest period of time. The "fast take-off movement" (vertical take-off velocity, maximal knee angular velocity) is necessary for the execution of a long distance jump (Schwameder, 1993). From the factor analysis of variables that determine the technique of take-off in ski jumping ensues, that the criteria variables influencing the length of jumps were mainly associated with the in-run velocity and the vertical take-off velocity; the accuracy of take-off affects the length of the jumps only indirectly and latently (Vodicar & Jost, 2010).

Two other multivariate parameters are also important predictors of a jump's quality – a larger forward rotating angular momentum at take-off and a smaller angle between the body and the skis approximately 20 meters beyond the edge of the ramp (Brüggemann et al., 2002; Schwameder & Müller, 1995). At the end of this phase, the ski jumper has attained forward-rotating-body angular (somersault) momentum, which serves to retain the necessary velocity and the best initial conditions for execution of the early flight position. This angular momentum is created by an optimal balance between ballistic and aerodynamic take-off parameters (Schwameder et al., 2005). Analysis of early flight at the 1994 Lillehammer Winter Games indicated that less than 15% of the variance in total performance (distance jumped) could be explained by centre of mass (CoM) parameters at take-off (Arndt et al., 1995). Observation of ski jump competitors is used to determine parameters that influence the length of the jump. For this reason, observations are often aimed at the take-off phase of the best ski jumpers (Virmavirta & Komi, 1994). The complexity of the structure of movement results in high individual variability with respect to the execution of the basic ski jumping phases. Such variability can occur not only between performance groups but also within the groups (Janura et al., 2007; Vaverka et al., 1997; Virmavirta et al., 2005). The purpose of this study was to analyze body kinematics of the take-off and start of the early flight phase. Specifically, this study seeks to compare ski jumpers of different skill levels during different phases of the jump and determine the variability between and within the groups.

Methods

A total of 72 male ski jumpers on the large HS-134 m jumping hill participated in the 2009 World Championships in Liberec, Czech Republic. Out of 72 analyzed competitors, 30 were assigned to a condition based on the length of the jump (LJ) and were divided into three groups: (1) elite (E) (*n* = 10, LJ 128.5-135 m), (2) mediocre (M) (*n* = 10, LJ 115.5-117 m), and (3) poor (P) (*n* = 10, LJ 97-105.5 m).

Two digital cameras (Sony DCR-TRV 900, Tokyo, Japan) were used to conduct 2-D video analyses (50 Hz). The cameras were located perpendicular to the sagittal plane of the ski jumpers' movement at the take-off and early flight positions (Figure 1). Since the conditions on the jumping hill did not allow for three-dimensional (3-D) measurement, we opted for 2-D analysis in the sagittal plane. The image space was calibrated by a 1m arm cross-calibration frame placed in the plane of the movement at the beginning and end of the observed section. The length of a recorded sector was 9 m, and the image had a resolution of 640 × 480 pixels; i.e. a shift of the cursor by 1 pixel was equivalent to a magnitude difference of .014 m. The accuracy of the body angular values was quantified in a previous study; in the recorded sector of about 1.4 m, the magnitude of the relative error was .51%, and the absolute error was .22° (Janura & Vaverka, 1997). It is assumed that the errors of angle determination in this study are about 2° and, for the approximal angular velocity, of 20°/s. The data were manually digitized by an experienced researcher.

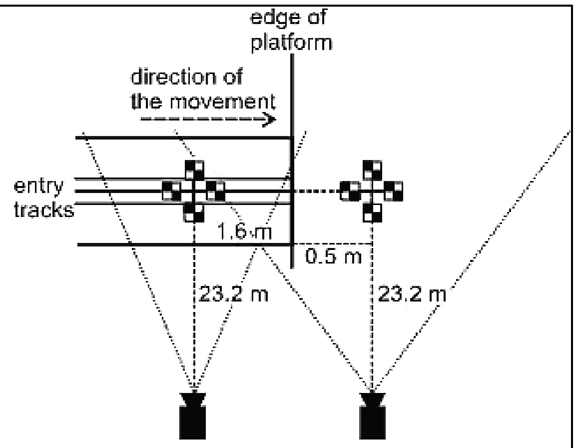

Figure 1
The cameras' set up

The origin of the global coordinate system was placed in the middle of the in-run tracks at the edge of the jumping hill. We assumed a symmetrical body position in the sagittal plane. A seven-link bilateral model was created based on nine joint points—tip and tail of the ski, ankle, knee, hip, top of the head, shoulder, elbow and wrist. The model included the following segments: foot and shank, thigh, trunk and head, arm, forearm and ski; the changes of body segment positions were determined with respect to a horizontal plane (Figure 2). Values of the segments' relative mass (Karas et al., 1990) were added to the relative mass of the skis and gear for the calculation of the ski jumper's CoM.

One-way ANOVA with Fisher's post-hoc test were performed (STATISTICA, Version 8.0, Stat-Soft, Inc., Tulsa, USA). Within-group variability was calculated with a CV, and the Friedman test was used to compare CVs between groups. The mean joint angular velocity was calculated as a ratio of the mean joint angle change and the time elapsed from the beginning to the end of the observed section. The CoM angle was calculated between the line passing the ankle joint and CoM and the horizontal plane. The power analysis, done for the sample size and the anticipated effect size, chose the power of .80 for the significant differences in the variables noted in this study. Any *p*-value less than .05 was deemed significant.

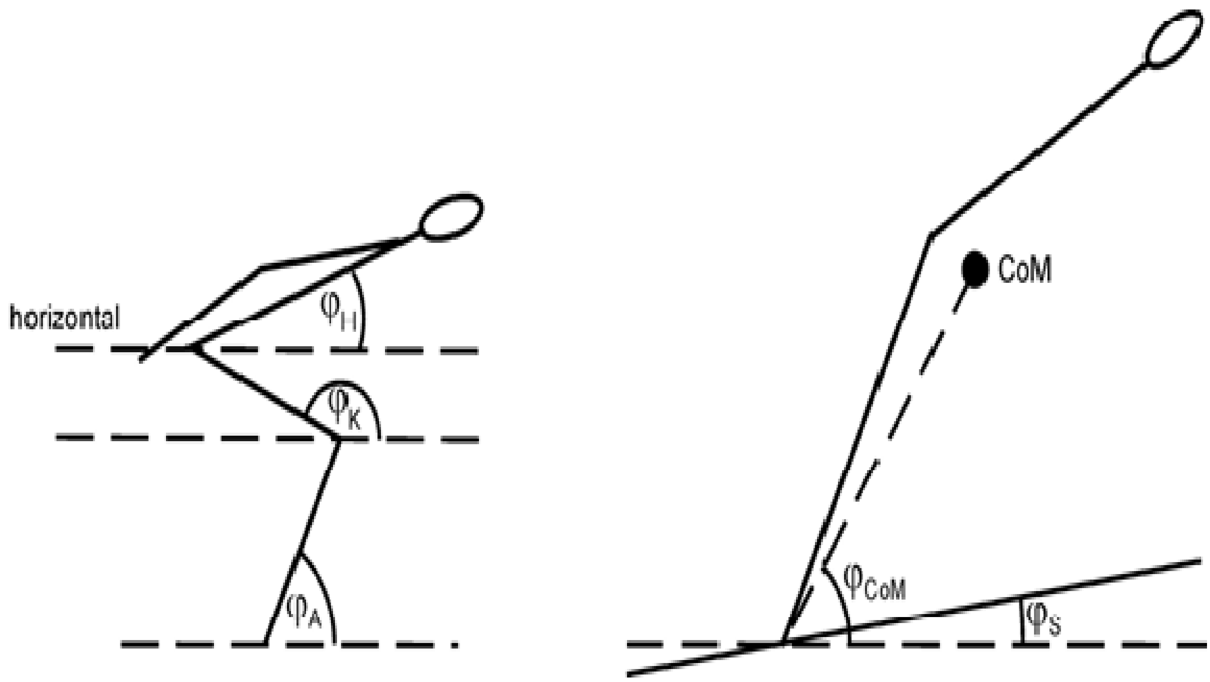

Figure 2

Measured angle parameters with respect to horizontal

Table 1

The measured parameters 2 m in front of and 5 m behind the jumping hill edge

Parameters	Elite Mean ± SD	Mediocre Mean ± SD	Poor Mean ± SD
LJ (m)	130.80 ± 2.15	116.00 ± 0.59	102.00 ± 2.83
v (m/s)	25.75 ± 0.10	25.75 ± 0.09	25.64 ± 0.11
φ_H -2 (°)	5.88 ± 4.12	7.92 ± 4.71	7.50 ± 4.33
φ_H 5 (°)	24.72 ± 4.65	26.91 ± 5.47	23.71 ± 4.25
ω_H -2 to 0 (°/s)	116.86 ± 33.52	99.01 ± 36.11	114.92 ± 22.57
ω_H 0 to 5 (°/s)	51.64 ± 20.67	59.57 ± 25.79	38.00 ± 36.66
ω_H -2 to 5 (°/s)	70.58 ± 18.35	71.03 ± 15.11	60.37 ± 24.81
φ_K -2 (°)	125.24 ± 3.24	129.40 ± 3.02	127.25 ± 6.07
φ_K 5 (°)	55.21 ± 6.30	58.68 ± 4.19	63.02 ± 3.17
ω_K -2 to 0 (°/s)	307.05 ± 29.41	301.08 ± 46.16	312.28 ± 23.41
ω_K 0 to 5 (°/s)	244.04 ± 29.88	249.61 ± 23.49	209.46 ± 28.99
ω_K -2 to 5 (°/s)	262.31 ± 23.91	264.55 ± 12.85	239.37 ± 16.41
φ_A -2 (°)	40.69 ± 3.67	42.00 ± 3.55	42.02 ± 5.12
φ_A 5 (°)	56.14 ± 5.56	57.67 ± 4.99	60.85 ± 4.69
ω_A -2 to 0 (°/s)	138.90 ± 28.44	129.91 ± 37.24	136.08 ± 35.61
ω_A 0 to 5 (°/s)	24.83 ± 28.11	29.29 ± 36.59	43.29 ± 30.82
ω_A -2 to 5 (°/s)	57.95 ± 20.36	58.64 ± 20.19	70.27 ± 24.61
φ_{CoM} -2 (°)	55.84 ± 3.43	56.51 ± 2.96	57.12 ± 2.96
φ_{CoM} 5 (°)	47.50 ± 4.19	50.91 ± 4.03	52.28 ± 3.55
ω_{CoM} -2 to 0 (°/s)	26.17 ± 19.64	43.27 ± 23.49	33.53 ± 26.87
ω_{CoM} 0 to 5 (°/s)	54.64 ± 23.27	47.34 ± 17.32	39.19 ± 17.44
ω_{CoM} -2 to 5 (°/s)	31.17 ± 16.36	20.93 ± 12.93	20.93 ± 12.93

LJ – length of jump, v – in-run velocity, φ_H – the angle between trunk and horizontal,
φ_K – the angle between thigh and horizontal, φ_A – the angle between shank and horizontal,
φ_{CoM} – the angle between CoM and ankle connection and horizontal,
ω_H – the trunk angular velocity, ω_H – the hip angular velocity,
ω_K – the knee angular velocity, ω_A – the ankle angular velocity,
ω_{CoM} – the CoM angular velocity, -2 – 2 m in front of the jumping hill edge,
-5 – 5 m behind the jumping hill edge,
-2 to 0 – the lap from 2 m in front of the jumping hill edge to the edge,
0 to 5 – the lap from the jumping hill edge to the 5 m behind the edge,
-2 to 5 – the lap from 2 m in front of the jumping hill edge to the 5 m behind the edge

Results

The values of the measured parameters are presented in Table 1. Figure 3 presents a graphic comparison of the E and P groups for three locations – 2 m in front of the edge, on the edge, and 5 m behind the edge of the jumping hill.

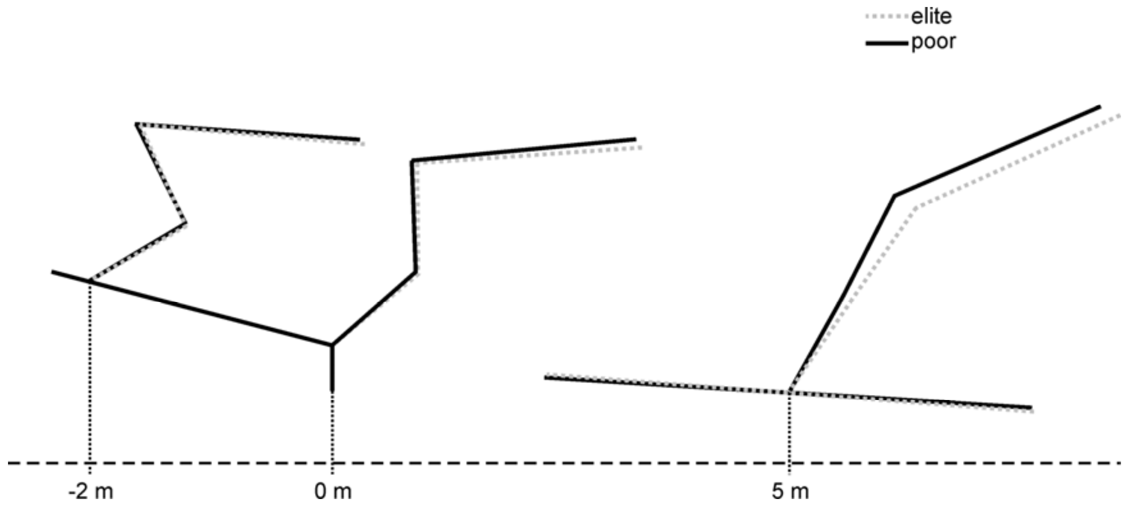

Figure 3
Graphic comparison of elite and poor quality jumpers at selected points of the analyzed section

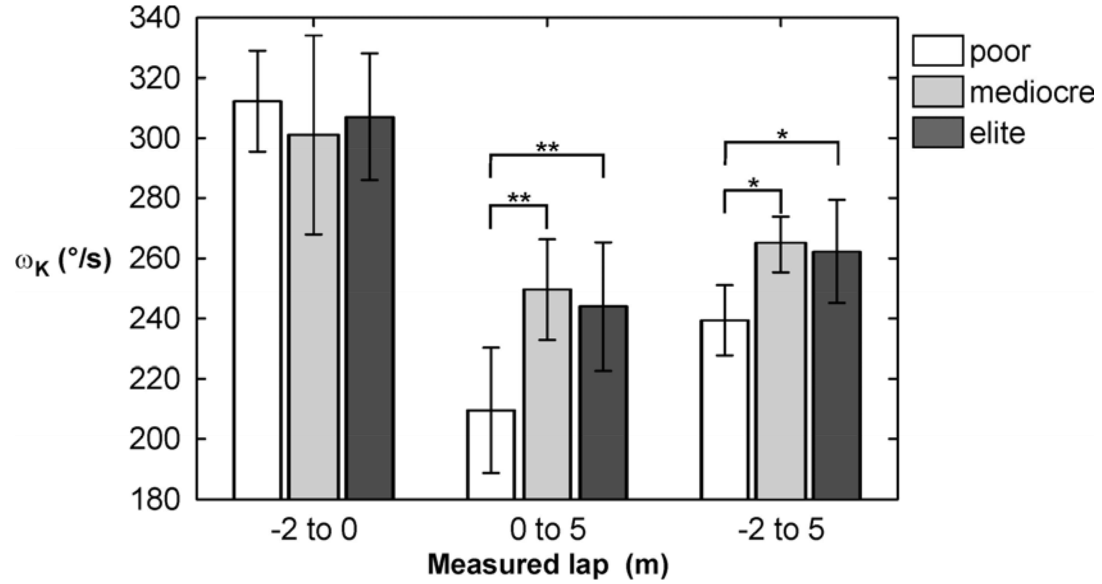

Figure 4
Comparison of changes in thigh position among groups of ski jumpers with different performance levels

The average in-run velocity of the competitors with poor performance scores was significantly lower ($p < .05$) than those of the other two groups. At 5 m behind the jumping hill's edge, there was a significant difference in the position of the thigh between the P and E groups. The P group had a larger angle of the thigh relative to horizontal ($p < .01$); moreover, the angular velocity of this segment in a section from 2 m in front of the edge to 5 m behind the edge was significantly smaller ($p < .05$) for the P compared to the E group (Figure 4). The CoM in the E group was shifted significantly more forward ($p < .01$) in the area behind the jumping hill's edge (Figure 5), as compared to group P.

There also was a difference in the thigh position at 2 m in front of the edge between groups E and M. Specifically, the angle of the thigh relative to horizontal was significantly larger ($p < .05$) in group M than in group E.

We found a significant difference in a tendency of practical importance for the position of the thigh at 5 m behind the jumping hill edge between groups P and M. The thigh angle to horizontal in this position was significantly larger for group P than for group M ($p < .05$). This was also shown in a forward movement of the thigh, for which the mean value of the movement in group M was larger than that of group P ($p < .01$).

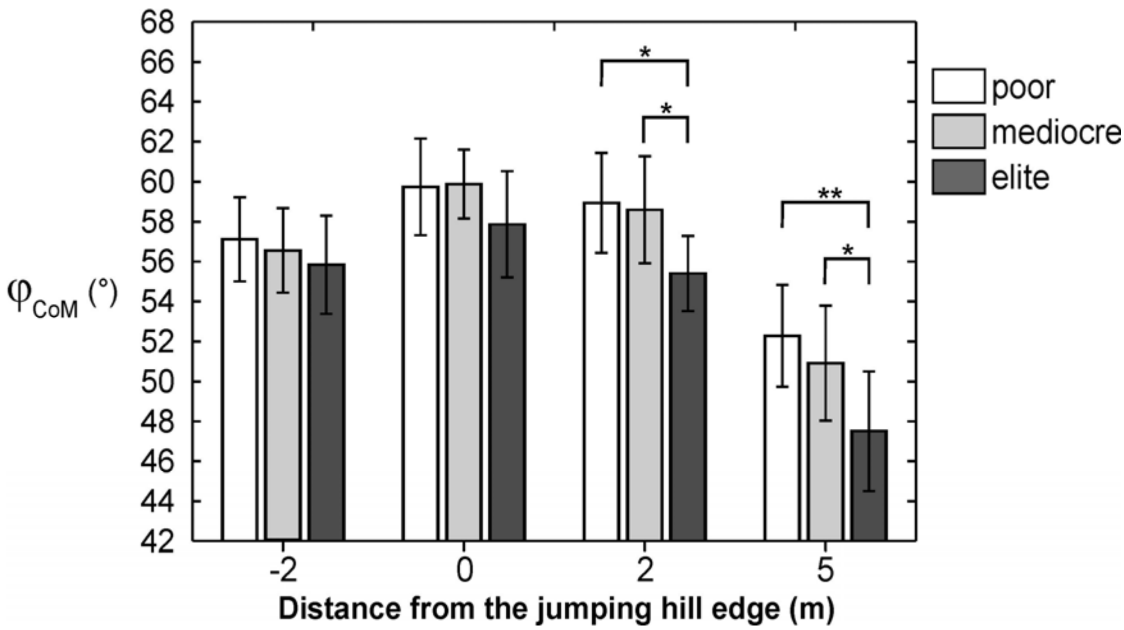

Figure 5
Comparison of CoM position in the whole analyzed section among groups of ski jumpers with different performance levels

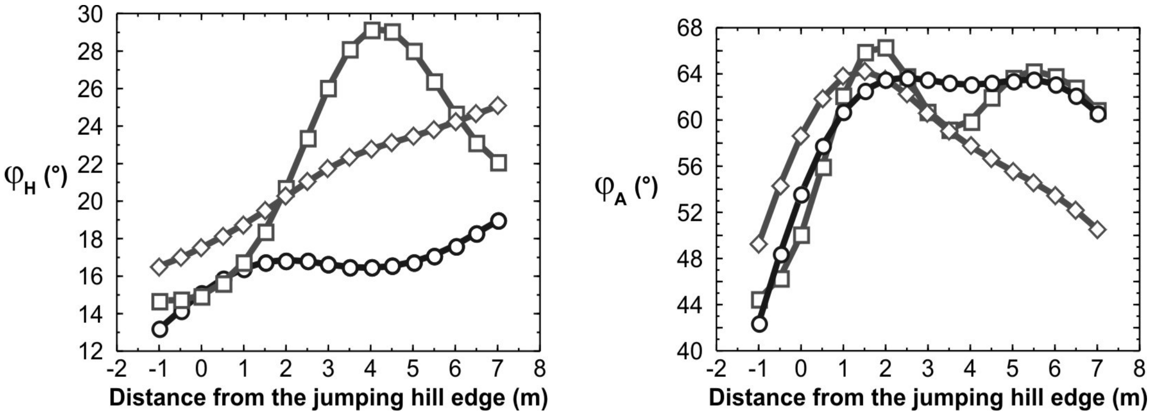

Figure 6

Comparison of the trunk and shank position changes of three ski jumpers with similar jump lengths

The variation of measured parameters within each group is large and there is no statistical difference ($p > .05$) in CVs among the groups. The CVs of the angles were less than 10% with one exception; the CV of the trunk angle at the beginning of the observed area ranged from 57.7% to 70.1%. The smallest variability in body segment position changes was in the shift of the thigh with respect to horizontal. Variability was larger for the position changes in the trunk and shank. The maximum CV values were found in the area 0-5 m behind the jumping hill edge (CV = 40.0-96.5% for position changes in the trunk and CV = 71.1-124.9% for the changes of the shank).

Ski jumpers with similar performance levels exhibited different take-off techniques. Figure 6 depicts a comparison of the angular changes for the trunk and shank positions for three ski jumpers (group E). For these ski jumpers, jump length ranged from 128.5 to 130.5 m.

Discussion

The group of jumpers with a short length of the jump (P) was significantly slower in the in-run velocity than were the two remaining groups of jumpers; groups E and M had similar mean values for the in-run velocity. The mean difference in in-run velocity, an important part of the resultant take-off velocity, contributed to differences among the mean jump lengths. We assume that the difference is caused not only by the technical execution of the in-run, but also by varying gear quality. A similar significant correlation between in-run velocity and length of jump was found in the final round of the 2006 Olympic ski jumping competition (Virmavirta et al., 2009).

The main finding in the present study consists in significant differences among groups with respect to the movement of the thigh behind the jumping-hill edge. Specifically, group E and group M are characterized by greater anterior movement in this area as compared to group P. The larger anterior movement in groups E and M was caused by a significant increase in thigh angular velocity. Changes in body segment positions at the final phase of take-off increase air resistance, which causes a decrease in jumpers' horizontal velocity (Virmavirta et al., 2005). Therefore, the anterior shift of the body found in the E group does not result in an increase in the angle joint value in the upper body. The findings for groups E and P in the current study are similar to those of Janura et al. (2001) in their study of the 2000 Junior World Championships. The authors found that competitors at a high performance level executed their take-off and early flight with larger changes in the knee-joint angle as compared to competitors at lower performance levels. Transition to the early flight phase is faster in the best jumpers compared to those of lower levels of performance; a faster transition is more favorable from the perspective of the actuation of aerodynamic forces (Arndt et al., 1995).

There was a statistically significant difference in the trunk position with respect to horizontal between groups E and M 2 m in front of the edge of the jumping hill. The athletes in group M demonstrated a more open body position than those in group E; the other angular differences were not statistically significant. Significant differences in the execution of selected parts of the jump were found not only between groups of jumpers with different performance levels but also within each group of jumpers with similar lengths of jump. Therefore, it is also necessary to study inter-individual differences in these groups when we compare the technique of ski jumpers with different performance levels (Schmölzer & Müller, 2005; Vaverka & Janura, 2002). Finally, there were no statistically significant differences in size among the groups of competitors with different performance levels.

The largest CVs for the angle characterizing the trunk position with respect to horizontal were derived from the jumper's body position at the end of the open kinematic chain; CVs for the angles measured for the lower extremities were smaller. The smallest variability of the thigh shift with respect to horizontal was in accordance with the results of the comparison of the competitors with different jump lengths. The magnitude of the rotation in the knee joint is a key factor for optimal take-off and early flight of the jump. The large within-groups differences among competitors with similar jump lengths suggest a practical solution, an individual approach to the evaluation of a ski jump. A study that offered similar conclusions found small correlations between the kinematic parameters and the length of jump and suggested individual optimal solutions for particular ski jumpers (Virmavirta et al., 2005; Vaverka, 2001).

In the current study, measurements of the joint angle were made with respect to horizontal. This decision was made because of the movements of the segments at the takeoff. For example, changes in the knee angle in poorer-quality competitors might cause an "under-cut" of the shank, which would be characterized by an ankle shift forward. This would affect the knee angle and result in an increase in angular velocity.

There were several limitations to the study. In practice, we do not encounter championships (competition round) with constant external conditions. The wind factor varied from 0.3-2.5 m/s, but a comparison of particular long-term performance levels of the jumpers and their classification in groups shows that the differential impact of wind among groups was not statistically significant for this division.

Further research should utilize the set of all measured kinematic parameters together with the internal preconditions of the ski jumpers (e.g., various anthropometric segment parameters, movement abilities and morphological entries).

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