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Take-off analysis of the Olympic ski jumping competition (HS-106 m)

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Abstract

The take-off phase (approximately 6 m) of the jumps of all athletes participating in the individual HS-106 m hill ski jumping competition at the Torino Olympics was filmed with two high-speed cameras. The high altitude of the Pragelato ski jumping venue (1600 m) and slight tail wind in the final jumping round were expected to affect the results of this competition. The most significant correlation with the length of the jump was found in the in-run velocity (r=0.628, p<0.001, n=50). This was a surprise in Olympic level ski jumping, and suggests that good jumpers simply had smaller friction between their skis and the in-run tracks and/or the aerodynamic quality of their in-run position was better. Angular velocity of the hip joint of the best jumpers was also correlated with jumping distance (r=0.651, p<0.05, n=10). The best jumpers in this competition exhibited very different take-off techniques, but still they jumped approximately the same distance. This certainly improves the interests in ski jumping among athletes and spectators. The comparison between the take-off techniques of the best jumpers showed that even though the more marked upper body movement creates higher air resistance, it does not necessarily result in shorter jumping distance if the exposure time to high air resistance is not too long. A comparison between the first and second round jumps of the same jumpers showed that the final results in this competition were at least partly affected by the wind conditions.

Keywords: Ski jumping; Take-off; Winter Olympic Games

1. Introduction

In ski jumping, the final result is mainly determined by the length of the jump. The different phases of the jump – in-run, take-off, flight, and landing together with its preparation – all contribute to its length. However, the take-off is considered to be the most important phase for the entire ski jumping performance since it determines the initial conditions (velocity, angle of take-off, angular momentum and position of the jumper/ski system) for the subsequent flight. A successful take-off requires maximal gain in vertical velocity along with maintenance of the release velocity. Mistakes during take-off cannot be corrected during the flight phase, but the benefits of a successful take-off action can be destroyed by mistakes during the flight. A comprehensive review concerning biomechanics research in ski jumping has been published recently by Schwameder (2008).

Debates on the importance of the take-off in ski jumping performance have tended to follow developments in flight phase aerodynamics (jumping suits, flight style, body weight, etc.). In fact, improvements in ski jumping aerodynamics have increased the jumping distance so much that the precise effect of various take-off parameters on jumping distance may have been masked by other interacting factors, including the contribution of lift and drag forces. The effect of body weight on jumping distance in ski jumping is widely known and discussed (e.g. Schmölzer and Müller, 2002; Müller et al., 2006), and this effect was well demonstrated in the 1994 Olympic large hill competition (Fig. 1, see also computer simulation in Table 2). In the 1994 Olympics, the well-adopted new V-flight style (first introduced a few years earlier) combined with low body weight seemed to contribute to the flight phase aerodynamics (and therefore the jumping distance) so much that the effects of the above mentioned take-off parameters could not be determined. Center of mass (CoM) velocities at take-off did not correlate with the jumping distance (Arndt et al., 1995). The more successful jumps in these Olympics were characterized by higher knee extension velocities and a more rapidly decreasing “somersault angle” towards the take-off edge. The somersault angle, defined by Arndt et al. (1995) as the angle between a line connecting the knee and shoulder joint centers and the horizontal plane, was used to describe the production of a forward angular momentum in the ski jumping take-off.

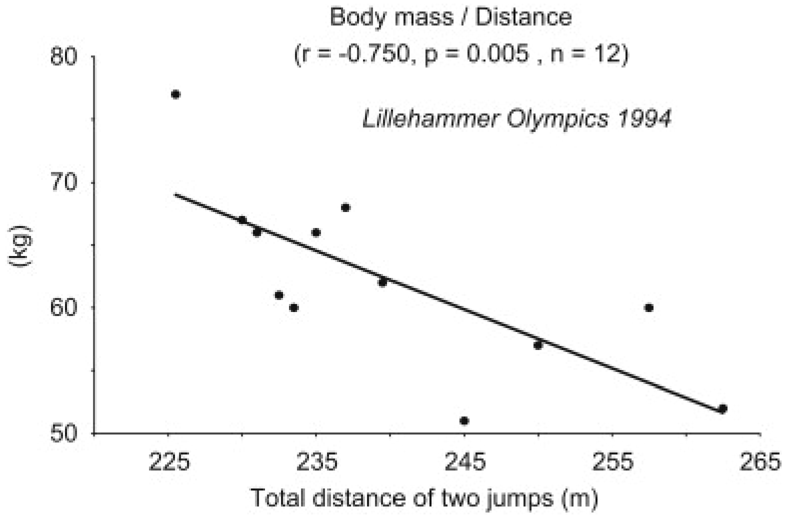

Fig. 1.

Correlation between the total length of two jumps and body weight of the best jumpers in the large hill competition of the 1994 Lillehammer Winter Olympics.

As the ski jumpers began to manipulate their body weight in an unhealthy way, the International Ski Federation (FIS) recognized the health hazards associated with extremely low body weight and decided to stop this development. The FIS set a rule whereby the ski length that a jumper is allowed to use in competition is determined by the body mass index (BMI). The maximum ski length, 146% of the jumper's body height, is only allowed if the jumper's BMI is 20 or more. The rule was introduced to make low body weight less of a concern for ski jumpers and less important for successful ski jumping performance.

The purpose of this study was to examine whether the contribution of take-off parameters to the jumping distance could be determined in an Olympic ski jumping competition. The study was one in a series of experiments performed at Winter Olympic Games since 1988 (Virmavirta and Komi, 1989). The projects are listed in Table 1, which shows that the current project (Torino, 2006) focused on the take-off phase. The particular interest in the take-off was based on the general assumption that the BMI rule, which was enforced in ski jumping in 2004, has indeed emphasized the role of the take-off. The Pragelato 106 m hill is classified as a small or normal hill, and is therefore well suited to a take-off study due to the smaller aerodynamic effects. The Pragelato ski jumping venue of the Torino Winter Olympics 2006 is located at an altitude of 1600 m, and there was a slightly changing tail wind during the competition. This is a combination that placed special demands on jumping in this particular competition.

Table 1.

List of ski jumping projects performed at the Winter Olympics since 1988 (e.g. Virmavirta and Komi, 1989; Arndt et al., 1995; Virmavirta et al.,2005)

Calgary 1988	Take-off force measurement
Lillehammer 1994	Early flight phase
Nagano 1998 (Hakuba)	Early flight phase
Salt Lake City 2002 (Park City)	Early flight phase
Torino 2006 (Pragelato)	Take-off phase

2. Methods

The take-off phase of all jumps in the individual competition of the HS-106 m hill at the Winter Olympic Games in Torino (Pragelato) was filmed with two high-speed video cameras (200 Hz) for 3D-analysis (Fig. 2). Cameras were synchronized with an audio sync pulse, and the image space was calibrated with a multiphase calibration method (Challis, 1995) in which the calibration frame (Peak E-67 standard, see Fig. 2) was captured in three different places to cover the entire area of interest in the Vicon Peak Motus motion analysis software. The jumps in which the images were clearly digitisable in both video cameras were considered satisfactory, and thus a total number of 42 and 28 jumps were included in the analysis for the first and second competition rounds, respectively.

Fig. 2.

Camera views for 3D video analysis.

The 3D model of the jumper's body consisted of 7 unilateral segments, assuming that the action of both sides of the body was symmetrical. The 3D coordinates of the joint centers were calculated from the manually digitised data. The segment parameters used for determination of the body CoM were taken from the data of De Leva (1996; adapted from Zatsiorsky-Seluyanov's segment inertia parameters, 1990). Linear and angular velocities were computed from the displacement data by using finite differences between next and previous positions of the digitised points. The kinematic data were smoothed using a fourth-order (0-lag) low-pass Butterworth filter with a cut-off frequency of 8 Hz.

Evaluation of the 3D DLT calibration accuracy showed only small errors between the reconstructed control point coordinates and the known control point coordinates (2.2, 1.6, 2.2 m) of the calibration frame (mean square errors of 0.426%, 0.648% and 0.556% for X, Y and Z coordinates, respectively). The difference between the distance of the computed and known locations of the fixed control points for the entire 6 m take-off table distance was only a few millimeters. Successful calibration was well demonstrated by the high correlation (r=0.749, p<0.001, n=70) between the officially measured in-run velocity and the average velocity of the body center of mass determined from the digitized data during the take-off (6 m).

The effects on jumping distance of low air density (induced by high altitude), as well as body mass and tail wind, were examined by applying the *computer simulation* (Virmavirta et al., 2001) model to the complete ski jumping performance (Table 2). Input parameters (e.g. take-off force values, drag and lift coefficients for the in-run position (C_d, C_l) and the flight phase) were derived from a wind tunnel experiment of one jumper participating in this competition. Different angles and angular velocities were calculated for different joints (hip, knee) and segments (shank, upper body), and the velocity components parallel and perpendicular to the take-off table were also determined. In the analysis, the take-off phase was divided into two separate parts (6–3 m and 3–0 m before the release instant), which represented the early and late take-off phases.

Table 2.

Computer simulation of the effects of body mass, altitude and wind on jumping distance in a reference jump of 102 m with the Pragelato HS-106 m hill profile information.

	Mass (kg)	No wind		Tail wind 1 m/s	
		Jump distance (m)	**Speed (km/h)**	**Jump distance (m)**	**Speed (km/h)**
Air density 1.20 kg/m^3 (sea level)	72	102.0	86.69	98.2	86.92
	71	103.2	86.66	99.7	86.89
	70	104.5	86.63	101.0	86.86
	69	105.8	86.59	102.4	86.83
	68	107.0	86.56	103.7	86.79
Difference	4	5.0	0.13	5.5	0.13
Air density 1.06 kg/m^3 (1600 m)	72	102.0	88.86	98.7	89.06
	71	103.2	88.83	100.1	89.03
	70	104.4	88.79	101.3	89.01
	69	105.6	88.76	102.6	88.98
	68	106.7	88.73	103.8	88.94
Difference	4	4.7	0.13	5.1	0.12

In this competition, none of the best jumpers after the first competition round were placed among the best in the final standing, which is very unusual. It was assumed that the final results were at least partly influenced by a slight tail wind during the last jumps in the final round. To estimate the effect of wind on the final results, an additional comparison was performed between the first and second jumping rounds for the best jumpers. Statistical analysis was also performed to determine linear correlations between the measured variables and the distance jumped. In addition, jumpers of different performance levels were divided into subgroups and compared. A linear regression analysis was applied to both jumping rounds and different subgroups separately to determine how different variables predicted the jump length.

3. Results

The computer simulation in Table 2 shows the effects of body mass, altitude and wind on jumping distance in a reference jump of 102 m with the Pragelato HS-106 m hill profile information. A decrease of 4 kilos in the jumper's mass (including the equipment) increased the jumping distance by 4.7–5.0 m. Considerably less speed (88.86–86.69 km/h) was needed to achieve the same reference jump distance of 102 m at sea level. High altitude provided a small advantage to heavier jumpers, and the effect of a steady head or tail wind of 1 m/s was about 3.5 m for a jumping distance of 102 m (102.0–98.2/98.7 m at sea level and high altitude, respectively).

Fig. 3a shows correlations between the official in-run velocity and the jumping distance (r=0.628, p<0.001, n=50), as well as a comparison between the longest and shortest jumps. Jumpers' release velocity parallel to the take-off table was slightly correlated with jumping distance during the first jumping round (r=0.346, p=0.012, n=42). Good jumpers were more able to maintain their CoM velocity parallel to the tracks (Fig. 3b) during the take-off. There were no clear differences between good and poor jumpers in terms of take-off position (Fig. 4a). Fig. 4b shows that angular velocity of the hip joint of the best jumpers at the release instant from the take-off table was correlated with jumping distance (r=0.651, p<0.05, n=10). In Fig. 5a, the behaviour of the knee and hip joint angles of the selected good jumpers during take-off is presented. Two jumpers who differed the most from each other in their upper body movement were selected for special comparison in Fig. 5b (see also web site material where jumper K is animated on top of jumper A).

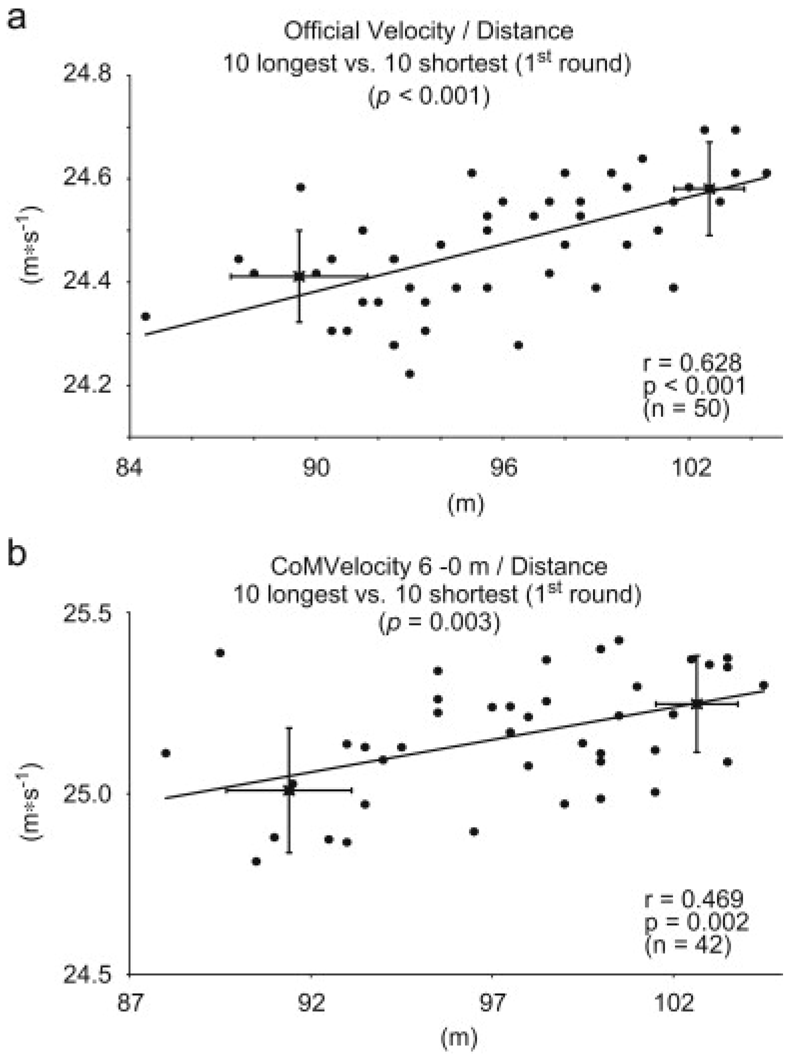

Fig. 3.

(a) Correlation between the official in-run velocity and the jumping distance, including a comparison between the longest and shortest jumps. (b) Correlation between the velocity of the body center of mass (CoM) during the last 6 m on the take-off table and the jumping distance. The longest and shortest jumps are also compared.

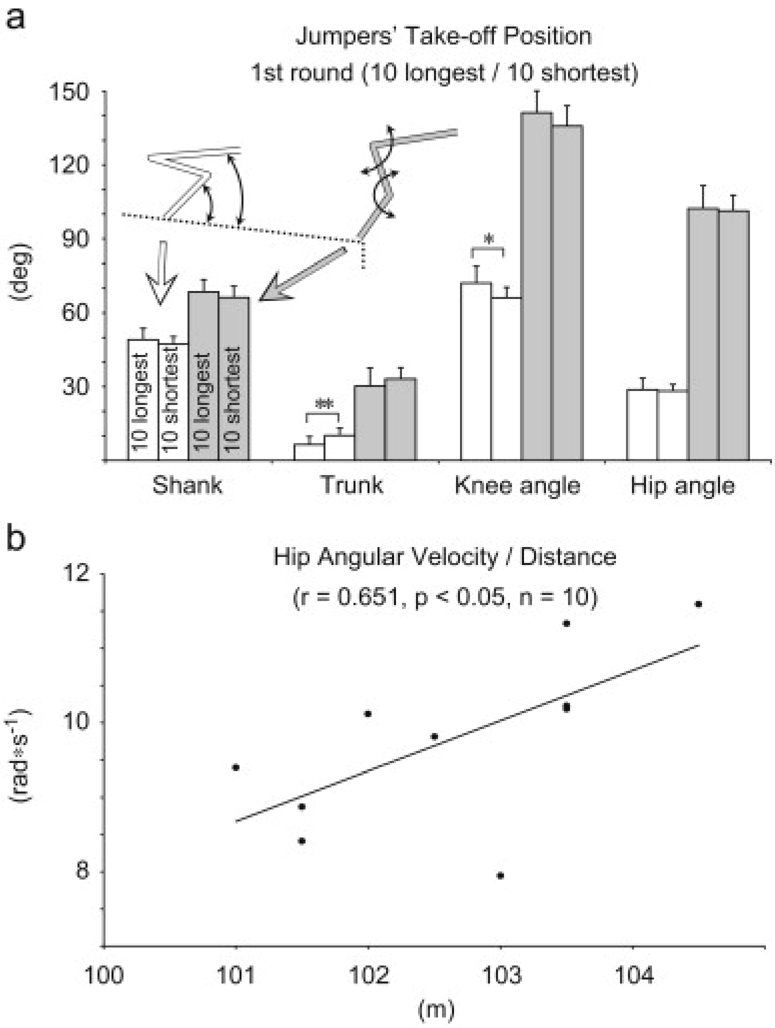

Fig. 4.

(a). Comparison of the take-off position (mean and standard deviation) between the best (10 longest, 1st bar) and worst (10 shortest, 2nd bar) jumpers. White bars refer to the initial take-off position and grey bars to the release instant (*p<0.05, **p<0.01). (b) Correlation between the angular velocity of the hip at the release instant and jumping distance of the best jumpers.

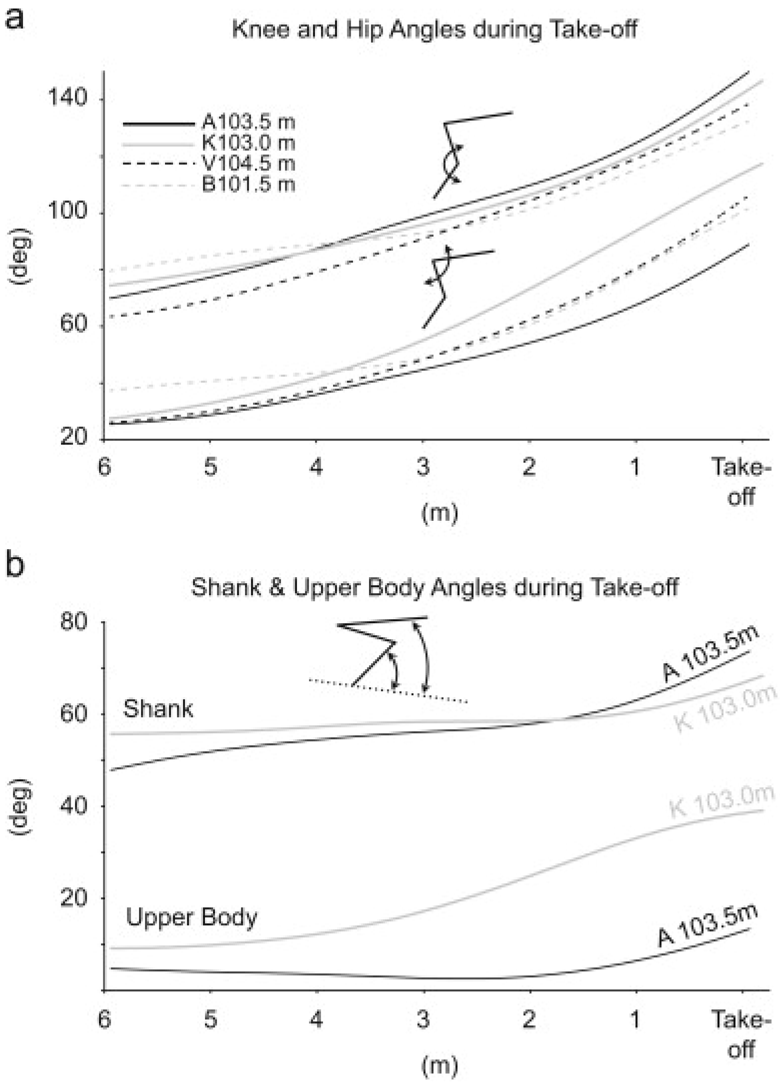

Fig. 5.

(a) Behaviour of the knee and hip angles of the selected good jumpers during the take-off. (b) Comparison of the shank and upper body angles of two jumpers (A and K). See also web site material.

A multiple regression analysis (stepwise) showed that jumpers' official in-run velocity and the average knee angle during the latter part of the take-off (3–0 m) accounted for 51.4% of the jump length variance in the first jumping round (n=42). The variables in the equation did not correlate significantly with each other and were normally distributed (Kolmogorov–Smirnov test). Official in-run velocity was also included in the stepwise regression model for the second round (r=0.435, p=0.01, n=30), but the R square value (coefficient of determination) did not increase significantly with any combination of variables (i.e. a simple regression equation with only one independent variable).

3.1. Comparisons between the 1st and 2nd jumping rounds

The relationship between body mass and jumping distance of the best jumpers after the 1st jumping round is shown in Fig. 6. The significant correlation found in the 1st round disappeared in the second round. Table 3 shows the interrelation between body mass, in-run speed and jumping distance for both jumping rounds separately. Since jumpers' in-run speed and body mass both affected the jumping distance, and they also correlated with each other, their multicollinearity effect in the regression analysis was avoided by calculating jumpers' kinetic energy including both variables. The only significant relationship between kinetic energy and the jumping distance was found for the best jumpers (n=10) in the first jumping round (r=0.674, p<0.05, simple regression equation with kinetic energy as the only selected variable), and the regression analysis did not reveal any other significant combination of predicting variables.

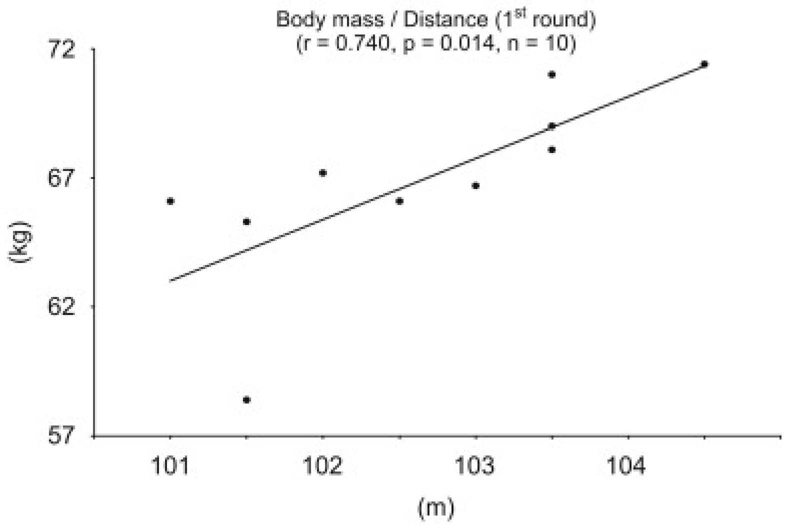

Fig. 6.

Correlation between body mass and jumping distance of the best jumpers in the first jumping round.

Table 3.

Correlations between in-run speed, body mass and jumping distance and body mass and in-run speed for the 1st and 2nd jumping rounds of all jumpers (n=50 in the 1st round and n=30 in the 2nd round), as well as the best (10 longest) and worst (10 shortest) jumpers.

	All jumps		**10 longest**		**10 shortest**	
	1st round	**2nd round**	**1st round**	**2nd round**	**1st round**	**2nd round**
Speed/distance	**0.628*****	**0.418***	0.609	−0.222	0.093	−0.154
Mass/distance	0.130	0.149	**0.740***	−0.293	−0.488	−0.316
Mass/speed	**0.458*****	**0.684*****	**0.715***	**0.817****	−0.013	0.500
Body mass (kg)	65.5±4.3	65.8±4.4	66.9±3.6	66.8±3.8	65.1±4.3	64.6±4.9
Body height (cm)	178.2±5.1	178.4±5.4	179.5±4.0	179.2±4.1	177.9±6.0	176.6±6.4

Significant values are in boldface (*p<0.05, **p<0.01, ***p<0.001).

There were no differences in the take-off position of the best jumpers between jumping rounds (Fig. 7a). Average angular velocities of the knee and hip joints as well as the shank and upper body during the first (6–3 m) and last (3–0 m) phases of the take-off also showed no differences between jumping rounds (Fig. 7b and c).

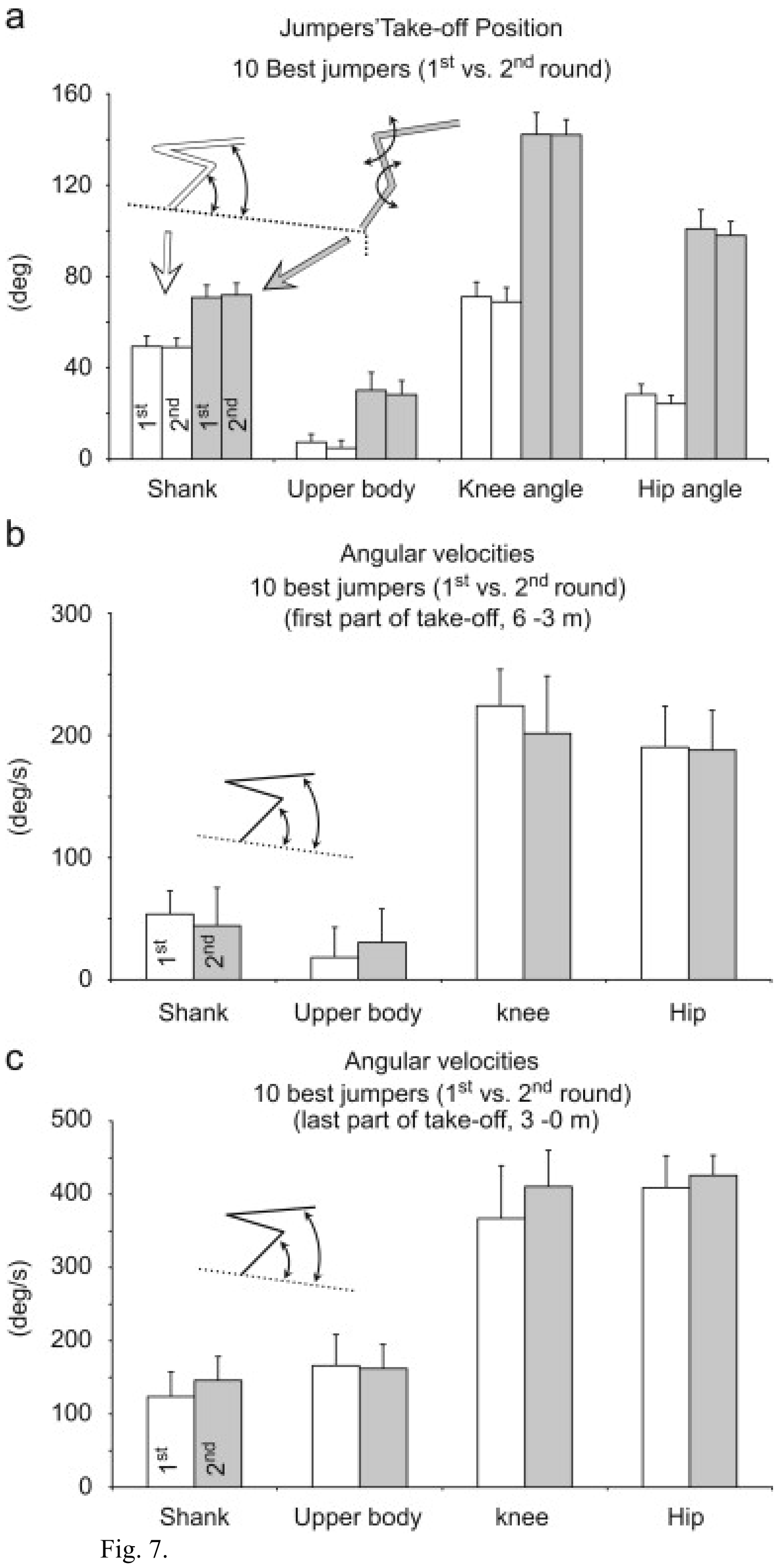

Fig. 7.

(a) Comparison of the take-off position (mean and standard deviation) of the best jumpers between the 1st and 2nd jumping rounds. White bars refer to the initial take-off position and grey bars to the release instant. (b, c) Comparison of the different average angular velocities (mean and standard deviation) of the best jumpers between the 1st (white bars) and 2nd (grey bars) jumping rounds. (b) Shows the first part of the take-off (6–3 m on the take-off table) and (c) the last part of the take-off (3–0 m).

Fig. 8a shows the first and second jump of the jumper V who was leading the competition after the first round and placed 10th in the final standing. Different angles of the same jumper from the 1st and 2nd jumping rounds are superimposed in Fig. 8b.

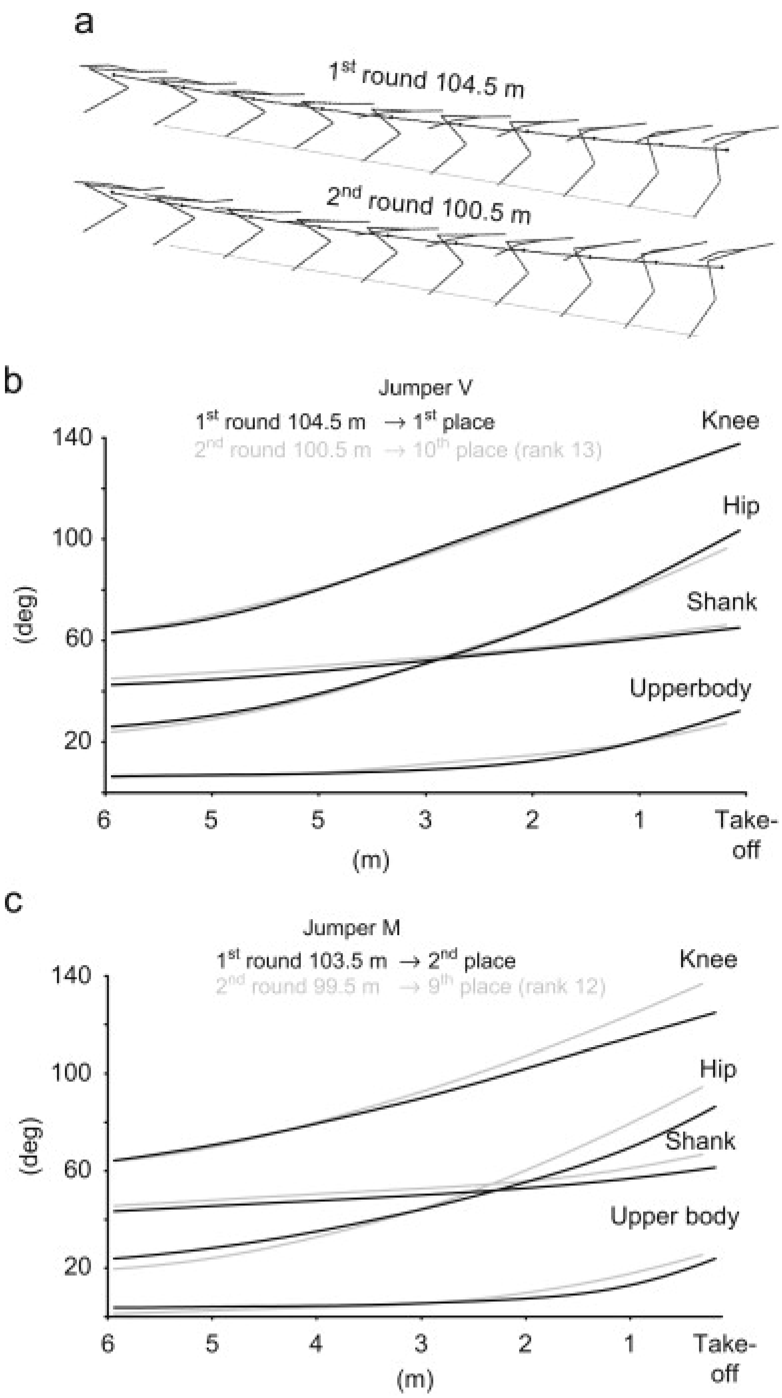

Fig. 8.

(a–c). Comparison between the 1st and 2nd round jumps of the selected good jumpers. See also web site material.

The jumper who was second after the first round and placed 9th in the final standing showed a different technique in his second jump (Fig. 8c). The jumper who was in joint second place after the first round also showed differences, especially in the timing of the take-off, which is well demonstrated in the video clip attached in the web site material.

4. Discussion

The present results clearly showed that the importance of low body weight to the final jump distance was reduced after the BMI rule was set (Fig. 1 and Fig. 6). The significant correlation between body mass and jumping distance observed in the first round disappeared and even became negative in the second round (Table 3). This may be due to the altered wind conditions (slight tail wind, average 0.8 and 1.5 m/s for the 1st and 2nd round, respectively) for the last jumpers in the final round. As seen in the computer simulation, a tail wind is known to cause more problems for heavier jumpers (difference in jumping distance at different altitudes of 5.0/4.7 and 5.5/5.1 m for no wind and a tail wind of 1 m/s, respectively), which could at least partly explain the differences between the first and second rounds.

The interrelationship between in-run speed, jumping distance and body mass in Table 3 seems to be dependent on the performance level of the jumpers analysed. The worst jumpers in this competition (10 shortest) showed no significant correlation in any of the three parameter combinations, probably because of the large variations in their performance techniques. It is clear that heavier jumpers generate slightly higher speeds during the in-run (Table 2 and Table 3), and a correlation was found between body mass and in-run speed for the best jumpers. Since the very best jumpers exhibit very small differences in their performance technique, they are able to utilize the small advantage of greater body mass during the in-run. The combined effects of jumpers' in-run speed and body mass on jump length were emphasized by the correlation between jumpers' kinetic energy at the release instant from the take-off table and jumping distance. The possible effect of the tail wind at the end of the second round is well demonstrated by the correlations between in-run speed and jumping distance and between body mass and jumping distance for the best jumpers (10 longest).

It is well known that the in-run speed is the most important factor affecting the jumping distance in ski jumping, but it was still a surprise to find such a strong correlation (Fig. 3a) between the official in-run velocity and jumping distance in Olympic level ski jumping. This most likely means that the good jumpers simply had smaller friction between their skis and the in-run track and/or the aerodynamic quality of the in-run position was better in these jumpers. The aerodynamic quality of the jumpers' in-run position is dependent on the reference area and drag coefficient of the jumper's body. Both these parameters depend on size, shape, configuration and orientation of the jumpers' body in the crouch position. In-run and take-off aerodynamics in ski jumping are discussed in more detail by Virmavirta et al. (2001). In this competition, good jumpers were more able to maintain their CoM velocity parallel to the tracks during the take-off (Fig. 3b). The effect of in-run speed was also emphasized in the regression analysis, where speed and average knee angle accounted for 51.4% of the jump length variance in the first jumping round.

The differences between take-off positions of good and poor jumpers were very small (Fig. 4a). Good jumpers had a slightly lower upper body position and a more extended knee. However, the angular velocity of the hip joint of the best jumpers correlated with the jumping distance in the first jumping round (r=0.651, p<0.05, n=10). Upper body movement is considered to be very critical in the ski jumping take-off because rapid hip extension is thought to cause high air resistance due to the upright position of the upper body. For achieving a proper flight position Schwameder (2008) described that "ski jumpers have to produce forward-rotating angular momentum about the center of mass during the take-off". This is possible when the ground reaction force vector passes behind the center of mass and creates a needed moment arm. In the experiments of Schwameder and Müller (1995) all the jumpers showed forward-rotating moment during the take-off, the average moment being 66±10 Nm and the final angular momentum at the release instant 19±3 Nms. Moreover, aerodynamic drag force on the jumper/skis system tends to produce a backward-rotating angular momentum (Schwameder, 2008) which is highly dependent on the jumper's upper body movement. The good balance between these opposite moments of force is a major challenge for the jumper in successful performance. The best jumpers in this competition exhibited very different techniques in terms of their upper body movement, but were still able to jump approximately the same distance. It seems that upper body movement does not necessarily result in shorter jumping distance if the jumpers are able to create sufficient forward angular momentum during the take-off as suggested by Schwameder (2008). This prevents the exposure time to high air resistance from being too long.

In Fig. 5a, where the behaviour of the knee and hip angles of the selected good jumpers during the take-off is presented, it is important to note the large variety of techniques used by different jumpers to achieve approximately the same distance. When two jumpers (A, K) who differed the most from each other in their upper body movement are selected for comparison (Fig. 5b), it is difficult to believe that they jumped almost the same distance. In Fig. 5b, the relationship between upper body and shank movements is also shown. It is known that by keeping the shank angle (relative to the take-off table, presented in Fig. 5b) the same, especially during the early stages of take-off, the jumpers are better able to produce force against the surface and move their upper body forward (Virmavirta and Komi, 1994). Accordingly, the shank segment serves as a support for the thigh segment to rotate clockwise (seen from the right side) around the knee joint. However, excessive forward motion of the shoulders (relative to the knee/ankle) is very often compensated by the increase of the upper body angle relative to the direction of motion (more upright position). This results in increase of the drag on the jumpers' body and tends to produce the backward-rotating angular momentum as mentioned above and also by Schwameder and Müller (1995). When the upper body position remains the same, as occurs for jumper A in Fig. 5b, the shank angle must increase in order to balance the forward motion during the rapid knee extension. This is a very crucial phase in the ski jumping take-off when the take-off forces should be produced against the surface. Both take-off techniques in Fig. 5b provided a good result in this competition, which certainly increases the interest in this sport. Special conditions in this competition (i.e. small hill, high altitude and tail wind) probably allowed exposure to high air resistance without any great loss in jumping distance. High altitude gives a small advantage to heavier jumpers, but it is probably more important to understand that high altitude does not favor low body weight as has been assumed. The effect of high altitude on ski jumping performance has been discussed in more detail previously (Virmavirta et al., 2005).

Fig. 7a–c show that the average angular parameters of the best jumpers did not reveal any significant differences between the first and second jumping rounds. This might imply that the difference in jumpers' performance was not due to different take-off techniques. The jumper who was leading the competition after the first round showed a very consistent take-off in both jumping rounds, suggesting that his performance was influenced by the tail wind. However, the more detailed comparison in Fig. 8a–d also showed that there really were differences in the individual take-off techniques between jumping rounds. The jumpers in joint second place after the first round both seemed to have problems with the timing of their take-offs. On this basis, it can be stated that the final results in this Olympic ski jumping competition were at least partly affected by wind conditions.

It can be concluded that the body type of ski jumpers seems to have changed since the BMI rule was set (see Müller et al., 2006). The importance of jumpers' in-run speed was very clear in this study, but it was still surprising since the factors affecting the speed varied across the jumpers more than expected at the Olympic level. It was also interesting to see how many different techniques can be used to achieve good results in ski jumping, which certainly improves the interest in ski jumping among athletes and spectators. Although conclusions about the effect of wind on the results of this Olympic ski jumping competition would require more detailed wind information for individual jumpers, it is clear that wind conditions play an important role in ski jumping and at least partly affected the final results in this competition.

Wind conditions place large demands on the competition jury when attempting to guarantee equal conditions for all jumpers. One solution for minimizing the effect of wind on a single important competition could be the addition of one jumping round for the best jumpers in order to avoid the effects of chance on the final standings.

Conflict of interest statement

There are no potential conflicts which could inappropriately influence the authors' work.

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