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Take-off aerodynamics in ski jumping

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Abstract

The effect of aerodynamic forces on the force–time characteristics of the simulated ski jumping take-off was examined in a wind tunnel. Vertical and horizontal ground reaction forces were recorded with a force plate installed under the wind tunnel floor. The jumpers performed take-offs in non-wind conditions and in various wind conditions (21–33 m s^{-1}). EMGs of the important take-off muscles were recorded from one jumper. The dramatic decrease in take-off time found in all jumpers can be considered as the result of the influence of aerodynamic lift. The loss in impulse due to the shorter force production time with the same take-off force is compensated with the increase in lift force, resulting in a higher vertical velocity (V_v) than is expected from the conventional calculation of V_v from the force impulse. The wind conditions emphasized the explosiveness of the ski jumping take-off. The aerodynamic lift and drag forces which characterize the aerodynamic quality of the initial take-off position (static in-run position) varied widely even between the examined elite ski jumpers. According to the computer simulation these differences can decisively affect jumping distance. The proper utilization of the prevailing aerodynamic forces before and during take-off is a very important prerequisite for achieving a good flight position. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Aerodynamics; Ski jumping; Take-off; Wind tunnel

1. Introduction

The classic wind tunnel experiments of Straumann (1955) have given the basic information on aerodynamics of ski jumping. Since wind tunnel studies in ski jumping have concentrated on the flight or in-run phase in static situations they have considerably improved the understanding of the effects of aerodynamic lift and drag forces on jumping performance (e.g. Tani and Iuchi, 1971). However, due to the ballistic features of the ski jumping take-off the role of aerodynamics during take-off has been discussed but not documented. The difference found between a jumper's vertical take-off velocity calculated from film analysis and from the measured net take-off force has been explained by aerodynamic factors (Virmavirta and Komi, 1993). According to Vaverka et al. (1993) only 72–85% of a jumper's take-off capacity can be utilized in field conditions. The take-off time of 800 ms measured in simulated laboratory conditions (Virmavirta et al., 1997) does not match the short take-off time in actual ski jumping conditions (0.25–0.30 s, Virmavirta and Komi, 1993) and thus laboratory tests may not well describe true take-off performance. Wind tunnel experiments may be utilized in this regard, and therefore the purpose of this study was to examine the effect of aerodynamic forces on the force–time characteristics of the simulated ski jumping take-off performed in a wind tunnel. The effect of the measured variables on actual ski jumping performance was estimated by computer simulation.

2. Methods

The effect of wind on the force–time characteristics of the simulated ski jumping take-off was measured using two world-class ski jumpers (JA, JS) and one less-experienced junior jumper (ML) in a subsonic Göttingen-type closed-circuit wind tunnel (Laboratory of Aerodynamics, Helsinki University of Technology, Espoo, Finland). The tunnel cross-section and the maximum speed in the test area were 3.68 m^2 and 70 m s^{-1}, respectively. A low nominal turbulence (0.1%)

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in the empty test section was achieved by a large settling chamber with a contraction ratio of 13 and with a main flow velocity distribution of 0.12%. A Pitot tube connected to a Rosemount pressure meter was used to derive the wind velocity from the kinetic pressure. A boundary layer and blockage effect correction (correction factor 1.04 including the portion of boundary layer 3.4%) was applied to the measured kinetic pressure by using Maskell's correction method (Rae and Pope, 1984) based on average blockage during take-off ($\varepsilon = 0.25SA^{-1}$, where S is the blockage area of model and A is the area of tunnel test section). This allowed the true flow velocity to be calculated according to the following formula:

$$v = \sqrt{2q\rho^{-1}}, \tag{1}$$

where q is the kinetic pressure (Pa) and ρ is the air density ($\mathrm{kg\,m^{-3}}$). The air density, ρ, was calculated according to

$$\rho = p(RT)^{-1}, \tag{2}$$

where p is the air pressure (Pa), T is the air temperature (K) and R is the gas constant ($287.1\,\mathrm{J\,K^{-1}\,kg^{-1}}$). Vertical and horizontal ground reaction forces were recorded with a force plate installed under the tunnel floor (Fig. 1) during ski jumping take-offs in non-wind conditions as well as in conditions with different wind speeds ($21–33\,\mathrm{m\,s^{-1}}$). The non-wind conditions served as a reference "laboratory trial" for the other trials in different wind speeds. The take-off situation in the wind tunnel was carefully tested before the measurements and jumpers did not find any difficulties while taking-off with maximal effort. The wind tunnel floor was softened with the thin mattresses. The jumpers performed the simulated take-offs (4–6 in each condition) in the same way as in training. In the reference non-wind condition an assistant was used to support the jumper after toe-off as the take-off was directed up and forward. In order to simulate actual low-friction conditions where little or no horizontal (anteroposterior) forces can be produced, one jumper also performed a series of vertically directed take-offs. The aerodynamic lift and drag (air resistance) forces during the initial take-off position (static in-run position) were read from the vertical and horizontal ground reaction forces. The force plate arrangement also enabled the lift and drag forces of the flight simulation without skis to be recorded.

EMG activities from the three selected muscles (Vastus lateralis, Gastrocnemius and Gluteus) of one jumper were recorded by a Paromed Datalogger attached to the jumper's lower back under the jumping suit. The Paromed Datalogger system uses pregelled single-use ECG electrodes (Ag/AgCl, 10 mm diameter and 25 mm interelectrode distance, manufactured in the EU by Niko Surgical Ltd., UK). The electrodes were placed longitudinally on the surface of the muscle belly.

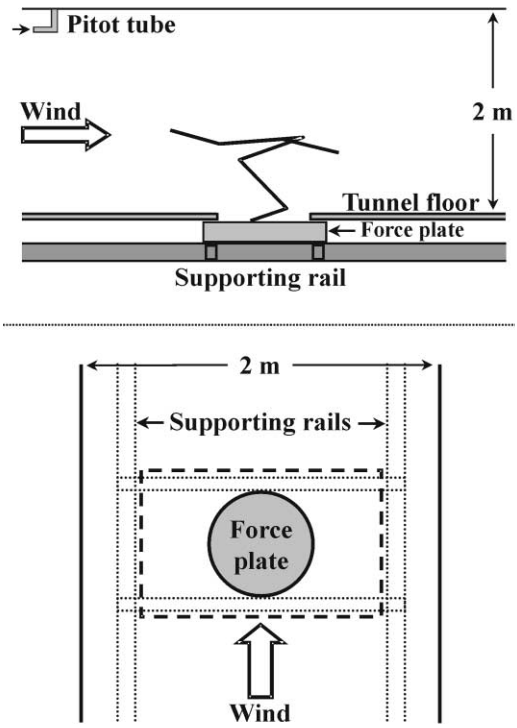

Fig. 1. Schematic illustration of lateral (upper) and overhead (lower) views of the force plate arrangement in the wind tunnel.

The pre-amplification factor in the vicinity of the electrodes is set by the manufacturer at 100 and the input impedance at 10 GΩ. The final EMG amplification was set at 1000 with low and high cut-off frequencies of 10 and 400 Hz, respectively.

2.1. Data processing

The force production time as well as the average and maximum net force levels were analyzed from the vertical ground reaction force signals. The average lift force of two jumpers during take-off was calculated by using equations for average acceleration, a, and for average force, F:

$$h = \tfrac{1}{2}at^2, \tag{3}$$

where h is the vertical displacement of the body center of gravity during take-off and t is the take-off time. After the solution of average acceleration the average take-off force could be calculated according to Newton's second law

$$F = ma, \tag{4}$$

where m is mass of jumper and his equipment. Thus, the aerodynamic lift force can be evaluated as the difference in average force between the non-wind and wind conditions. The air resistance of the initial take-off position (i.e. static in-run position) was read from the horizontal force component just before the take-off. The aerodynamic lift force during the same initial phase was calculated from the non-wind conditions as a reduction in vertical ground reaction force. The aerodynamic forces acting on the jumper during forward leaning ("flight position") were also calculable from the ground reaction forces.

In the EMG measurements the average muscle activities (aEMG) were compared between the non-wind condition and the wind condition of $27\,m\,s^{-1}$. Owing to the possible effect of the Datalogger on the air stream around the jumper ("hunchback") this comparison was done separately from the other trials.

The take-offs were filmed with one high-speed video camera (peak performance) from the side through a window in the tunnel door. The mechanical model of the jumper consisted of eight segments (head, trunk, thigh, shank, foot, arm, forearm + hand) and was used mainly to characterize possible differences in movement patterns between the non-wind and wind conditions.

2.2. Computer simulation

The results were fed into Aquila ski jumping simulator. The Aquila is a time-discrete second-order CoG-point simulator modeling the complete ski jumping performance: the in-run, take-off, transition to flight and flight. The time step used in the simulator was 0.02 s. The Aquila simulator has been tested against the Finnish Artillery six-degrees-of-freedom (6DOF)-simulator and found to be very accurate. The following parameters were used as input: Total mass of the ski jumper, reference area of the ski jumper including skis (therefore it is not the same as the area used for tunnel blockage correction which involves the area fitted for the take-off), coefficient of ski friction, take-off force profile with max value, drag (C_d) and lift (C_l) coefficients for the crouch in-run position, and $C_d(t)$ and $C_l(t)$ for the flight phase.

In the statistical analysis the trials in non-wind conditions were compared to the trials performed in the different wind conditions separately for each subject with two-tailed t-test for samples with equal variances.

3. Results

The means of all the take-off variables for all three jumpers in three different wind conditions are presented in Table 1. The wind conditions resulted in a significant decrease in take-off time in all jumpers. The decrease was 11.3, 13.9 and 14.4% for jumpers JA, JS and ML, respectively, at the highest wind speed. Fig. 2 shows an example of the vertical force curves in non-wind and wind conditions. A vertically directed take-off (labeled as a vertical jump in Fig. 2) emphasized the short take-off time found in wind conditions. The decrease in take-off time of jumper JA was significant with the Datalogger as well (457 ± 13 ms, 432 ± 9 ms in non-wind and wind condition, respectively). The peak take-off forces were not affected by the wind (Table 1), except for subject JA at the two highest wind speeds. The average lift force during take-off was 72 and 100 N for jumpers JA and JS, respectively. EMG activities did not show any major differences between the non-wind and wind conditions as demonstrated by the time-normalized presentation in Fig. 3. Columns titled "in-run position" in Table 1 show the aerodynamic forces of the jumpers' initial take-off position. Jumper JS showed much higher drag (59.7 ± 6.3 N, wind speed $27\,m\,s^{-1}$) and lift values (50.4 ± 3.2 N) than jumpers JA and ML (39.2 ± 6.9 N, 22.3 ± 0.8 N and 42.8 ± 2.3 N, 5.2 ± 2.2 N, respectively) at every wind speed. These aerodynamic forces were also strongly interrelated for jumper JS ($r = 0.942$, $p < 0.001$). Fig. 4 shows a comparison of the upper body angle from the horizontal between jumpers JA and JS.

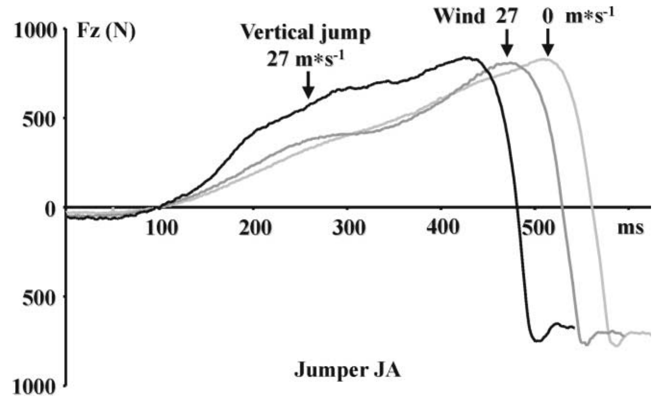

Fig. 2. Vertical take-off force curve of one jumper in different wind conditions. In the vertical jump, take-off was directed straight upward. The zero force level is set to the jumper's body weight.

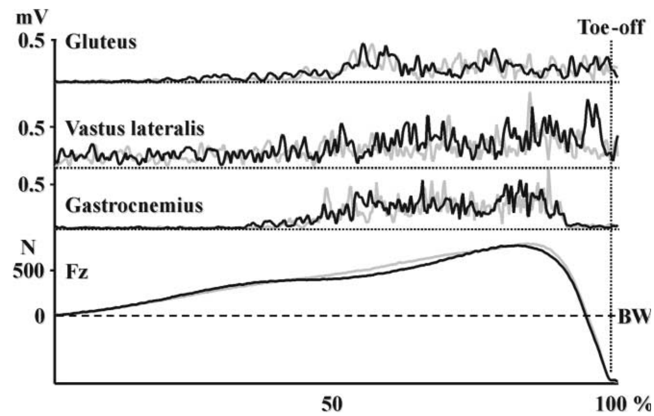

Fig. 3. Time-normalized EMG patterns of one jumper in the non-wind and in wind (bold) conditions of $27\,m\,s^{-1}$.

The vertical take-off velocity derived from the net impulse in the non-wind condition (JA $2.68\,m\,s^{-1}$, JS $2.63\,m\,s^{-1}$ and ML $1.97\,m\,s^{-1}$) decreased significantly

Table 1
Means of all take-off variables for three jumpers in three different wind conditions. Significant differences between non-wind and wind condition are shown by footnotes a–c

	Wind ($m\,s^{-1}$)	Take-off time (ms)	Max force (N)	Average force (N)	In-run position		"Flight"
					Drag (N)	Lift (N)	Lift/drag (N)
JS	0	410 ± 27	747 ± 20	443 ± 39			
	27	374 ± 17^{a}	731 ± 30	446 ± 37	59.7 ± 6.3	50.4 ± 3.2	
	33	353 ± 11^{b}	722 ± 30	448 ± 41	81.4 ± 4.1	70.3 ± 1.5	
JA	0	457 ± 13	852 ± 27	423 ± 16			
	27	422 ± 7^{c}	816 ± 44	432 ± 16	39.2 ± 6.9	22.3 ± 0.8	236/216
	33	405 ± 15^{c}	740 ± 67^{a}	416 ± 28	72.8 ± 10.9	18.8 ± 3.1	
ML	0	298 ± 21	718 ± 18	382 ± 28			
	27	264 ± 37^{a}	741 ± 40	381 ± 47	42.8 ± 2.3	5.2 ± 2.2	222/188
	30	260 ± 16^{b}	705 ± 24	347 ± 17^{a}	54.3 ± 2.0	8.2 ± 5.5	

[a] $p<0.05$.
[b] $p<0.01$.
[c] $p<0.001$.

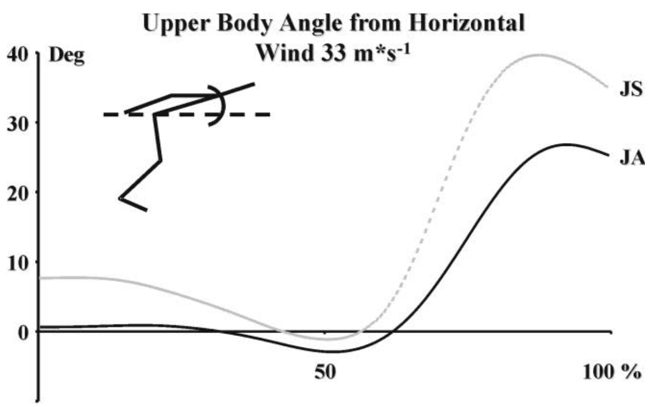

Fig. 4. Comparison of the upper body angle from the horizontal between jumpers JS and JA in wind conditions of $33\,m\,s^{-1}$.

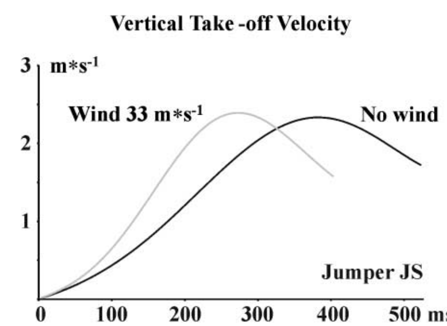

Fig. 5. Vertical take-off velocity of the body's center of mass for jumper JS in non-wind and wind conditions.

for all jumpers (JA $2.34\,m\,s^{-1}$, JS $2.29\,m\,s^{-1}$ and ML $1.72\,m\,s^{-1}$, $p<0.001$) at the highest wind speed. The same vertical take-off velocity calculated for the body's center of mass from the video analysis did not change with wind speed (Fig. 5).

Table 2
Comparison of two jumpers JA and JS with typical parameters in Lahti K114 hill profile

	C_d in-run	C_l in-run	$V_{V_{take-off}}$ ($m\,s^{-1}$)	$V_{official}$ ($m\,s^{-1}$)	Jump length (m)
JA	0.082	0.028	2.55	25.6	120
JS1	0.136	0.117	2.55	25.1	100.9
JS2	0.136	0.117	2.35	25.1	93.7

3.1. Comparison with computer simulation

The parameters of jumper JA were fed into the simulator as a reference. The official inrun velocity (photocell) was set to $92\,km\,h^{-1}$ ($25.6\,m\,s^{-1}$) by adjusting the starting gate. The flight aerodynamics was adjusted to give a reference jump of 120 m. The simulation results are presented in Table 2. In all cases the flight aerodynamics was kept the same. JS 1 had the same measured take-off force as jumper JA. If, however, the vertical take-off velocity for jumper JS is calculated from his own measured take-off force (case JS2 in Table 2) the final length of his jump is further reduced.

4. Discussion

The significant decrease found in the take-off time of all jumpers in the various wind conditions is the main finding of the present study. Because it is known that aerodynamic lift is close to zero in a good initial take-off position and is over 300 N in the flight position (see also Table 1), the lift force during take-off is expected to be somewhere between these two values. Therefore, the short take-off time in wind conditions can be regarded as resulting from a reduced load under the influence of aerodynamic lift. This means that in non-wind condition the load, that jumpers are working against, is their own

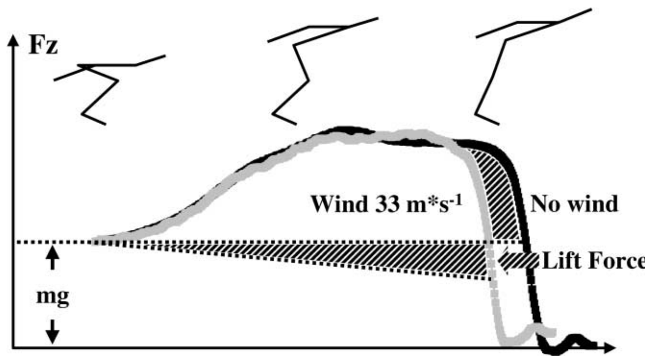

Fig. 6. Schematic illustration of the possible behavior of aerodynamic lift during ski jumping take-off.

bodyweight (*mg*) whereas in wind condition this load is reduced by the aerodynamic lift force ($mg–L$).

The maximum and average net forces did not change much with the increased wind speed and thus a lower vertical take-off velocity was expected in wind conditions with a decreased force production time. The minor decrease in the maximum force of jumper JA could be interpreted as the limited capacity of the muscles to produce force under a high contraction velocity. Since the jumpers' vertical take-off velocity was roughly the same in the non-wind and wind conditions as demonstrated in the comparison in Fig. 5, it is quite obvious that the aerodynamic lift force assists take-off by reducing load. However, based on the limited number of subjects in this study, the present results probably should not be generalized.

The behavior of aerodynamic lift during take-off remains masked when analysis focuses on the ground reaction forces, which include both take-off forces and aerodynamic forces. However, it is possible to solve the average lift force during take-off by using equations for average acceleration and thereafter for average force. The difference in average force between the conditions gave the average aerodynamic lift force of 72 and 100 N for jumpers JA and JS, respectively. These values are in good agreement with the lift forces in Table 1. In the schematic illustration presented in Fig. 6 the one possible behavior of aerodynamic lift is outlined by the shaded area under the initial bodyweight just before take-off. In wind conditions the shaded area compensates for the loss in impulse caused by the shorter take-off time with the same take-off force. The true progression of the lift force is not necessarily this evident towards the end of the take-off phase. The decrease in take-off time was further emphasized in the vertically directed take-off as the take-off force was exerted in the same direction as the aerodynamic lift force. It is probable that this kind of force production closely resembles take-off in field condition, where, owing to the low friction between skis and track ($\mu = 0.05$, Ward-Smith and Clements, 1983) all the force is exerted perpendicularly against the take-off table. However, from the jumpers' point of view the vertically directed take-off may feel strange as the wind moves them backwards after the toe-off (end of ground contact).

The aerodynamic quality of the jumpers' initial take-off position is shown in Table 1. The high air resistance of jumper JS at every wind speed certainly prevents him from achieving a high final inrun speed, which is the most important factor affecting jumping distance (Virmavirta and Komi, 1993). High air resistance creates also an unfavorably large lift force before the take-off as can be seen in Table 1. This lift is generated when the air goes under the upper body in an unfavorable inrun position (Fig. 4). The jumpers' different abilities to utilize aerodynamic lift during take-off is probably caused by the behavior of the air stream around the upper body before and during take-off. Jumper JS had a large upper body angle relative to the horizontal, which means that a greater frontal surface area was exposed to air resistance. A good lift-assisted take-off helps the jumper to obtain a proper flight position (forward leaning) right after take-off.

The limited computer simulation used in the present study revealed interesting features. The difference of 1.5 $\mathrm{km\,h^{-1}}$ in the measured velocity (photocells) and almost 20 m in jump length between JA and JS1 is mostly determined by the higher C_d value of JS during the inrun position. Furthermore, the 1% change in C_d of the reference JA results in a 0.03% change in photocell velocity and a 0.17% change in jump length. More significantly, a 1% change in photocell velocity results in a change of 5.7% in jump length.

It can be concluded that the aerodynamic lift caused by wind brings the simulated ski jumping take-off closer to field jumping conditions and helps the jumpers to perform take-off in the limited time on the take-off table more effectively than has been assumed. The reduced take-off time with minor changes in EMG and force levels emphasizes the explosiveness of the ski jumping take-off. The proper utilization of aerodynamic lift during take-off might also help the jumper to maintain the aerodynamic in-run position longer, which on the other hand would guarantee a high final in-run speed.

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