Ski Jumping Takeoff in a Wind Tunnel With Skis

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The effect of skis on the force–time characteristics of the simulated ski jumping takeoff was examined in a wind tunnel. Takeoff forces were recorded with a force plate installed under the tunnel floor. Signals from the front and rear parts of the force plate were collected separately to examine the anteroposterior balance of the jumpers during the takeoff. Two ski jumpers performed simulated takeoffs, first without skis in nonwind conditions and in various wind conditions. Thereafter, the same experiments were repeated with skis. The jumpers were able to perform very natural takeoff actions (similar to the actual takeoff) with skis in wind tunnel. According to the subjective feeling of the jumpers, the simulated ski jumping takeoff with skis was even easier to perform than the earlier trials without skis. Skis did not much influence the force levels produced during the takeoff but they still changed the force distribution under the feet. Contribution of the forces produced under the rear part of the feet was emphasized probably because the strong dorsiflexion is needed for lifting the skis to the proper flight position. The results presented in this experiment emphasize that research on ski jumping takeoff can be advanced by using wind tunnels.

Keywords: aerodynamics, takeoff force, force-time characteristics

Simulated ski jumping takeoffs are standard exercises for ski jumping takeoff performance and, owing to the low number of takeoff trials in one ski jumping training session, they are used mostly for overcoming the problems involved in the takeoff technique (e.g., anteroposterior balance). These simulated takeoffs are usually performed with training shoes, which may be one of the reasons why the takeoff time in this condition is always longer than in actual ski jumping. In contrast to normal training shoes, the ski jumping boots allow only limited plantar flexion, and this is thought to partly explain the shorter takeoff time with ski jumping boots (Schwameder et al., 1997; Virmavirta & Komi, 2001a). It has also been shown that, in a push-off without plantar flexion, as in speed skating with conventional skates, the knee cannot be fully extended (Van Ingen Schenau et al., 1987). This result was supported by Virmavirta and Komi (2001a), who found significant differences between the final takeoff positions performed with training shoes and jumping boots (114.3 ± 4.6°, 91.1 ± 3.0° and 167.6 ± 5.2°, 155.2 ± 3.9° for ankle joint and knee joint, respectively). In actual jumping hill conditions, the knee joint is never fully extended (e.g., Schwameder & Müller, 1995, 135.4 ± 5.6°, range 124.1–151.7°, and Virmavirta et al., 2009, 141.5 ± 8.4°, range 126.5–161.2°).

There may be other reasons as well to account for this difference in takeoff times. Although ski jumping takeoff is clearly ballistic, little attention has been paid to the effect of the aerodynamic forces on the takeoff action. Virmavirta et al. (2001) suggested that the aerodynamic forces acting on the jumper in the actual ski jumping could explain the time difference between the actual and simulated ski jumping takeoffs. Based on a series of wind tunnel experiments, they concluded that aerodynamic lift ($L$) assists jumpers by reducing the load (i.e., bodyweight $mg – L$) against which the jumpers are working in real ski jumping takeoff movement. As these experiments were performed without skis in the wind tunnel, the current study was designed to examine the effect of skis on the above-mentioned difference between takeoff conditions. It was assumed that this protocol would be more realistic and will be more comprehensive to characterize the differences between actual and simulated ski jumping takeoffs. In addition, the role of the skis can be examined more thoroughly in this comparison.

Methods

Measurements were made in a subsonic Göttingen-type closed-circuit wind tunnel (Laboratory of Aerodynamics, Aalto University, Espoo, Finland). Detailed information of the tunnel properties (e.g., turbulence, boundary layer, and blockage effect correction) is presented by Virmavirta et al. (2001). The true flow velocity could be calculated according to the following formula:
where $q$ is the kinetic pressure (Pa) and $\rho$ is the air density (kg·m$^{-3}$). The air density ($\rho$) was calculated according to

$$\rho = \frac{p(\text{RT})^{-1}}{}$$

where $p$ is the air pressure (Pa), $T$ is the air temperature (K), and $R$ is the gas constant (287.1 J·K$^{-1}$·kg$^{-1}$).

The tunnel cross-sectional area in the test section (Figure 1) was fairly small (3.68 m$^2$) and it was not known beforehand whether the tunnel would be high enough for the takeoffs with skis. Therefore, two small ski jumpers (heights and weights 174 cm, 57 kg, and 166 cm, 52 kg, for jumpers A and B, respectively) volunteered and gave written informed consent for the study. The athletes performed simulated takeoffs in the wind tunnel, first without skis in nonwind condition and then in conditions with different wind speeds. The same conditions were then repeated with skis. The takeoff situation in the wind tunnel with skis was carefully tested before the measurements and after the practice with short skis and low wind speeds (50–70 km·hr$^{-1}$) one of the jumpers was able to use his full-sized skis (255 cm) in wind speed of 105 km·hr$^{-1}$ (Figure 2, see also the video material). This jumper (A) showed much more consistent performance in consecutive trials (4–6) and therefore the more detailed results of force–time characteristics presented in this article are mainly from this particular jumper.

Takeoff forces were measured with the force plate installed under the wind tunnel floor (Virmavirta et al., 2001) and adjusted to be even with the surrounding cushions (Figure 1). With this arrangement, the force plate was bearing all the weight of the subject and the skis were still in contact with the surrounding surface, allowing no air to go under the skis. The airflow at the boundary surface of the floor was controlled by a perforated fence in front of the jumper. This was supposed to guarantee the proper behavior of the skis at the release instant. Signals from the front and rear parts of the force plate were collected separately, which made it possible to examine the anteroposterior balance of the jumpers during the takeoff. The output of the front/rear force components does not give the exact force distribution under the feet, but, as the jumpers’ initial takeoff position was carefully determined in the anterior–posterior direction on the plate, the changes in the balance could be analyzed reliably. The good balance between the fore and rear parts of the foot has been found to be one of the most important prerequisites for effective force production during takeoff in ski jumping (Virmavirta & Komi, 2001b). It was hypothesized that the dorsiflexion needed for lifting the skis to the proper flight position would limit the plantar flexion, which can be freely used in the simulated ski jumping takeoff without skis. According to this hypothesis, the contribution of the vertical force components under the rear part of the feet might become more prominent.

The force production time, as well as the average and maximum net force levels, were analyzed from the vertical ground reaction force signals separately for front and rear parts of the force plate. The takeoffs were videotaped (50 Hz) from the side through the window of the tunnel door. The mechanical 2-D model of the jumper consisted of eight segments (head, trunk, thigh, shank, foot, arm, forearm + hand), assuming that the action of both sides of the body was symmetrical, and the model was used mainly to characterize possible differences in movement patterns between the trials in different conditions. The 2-D coordinates of the joint centers were calculated from the manually digitized data, and the segment parameters were taken from the data of De Leva (1996; adapted from the Zatsiorsky–Seluyanov segment inertia parameters [Zatsiorsky et al., 1990]). The kinematic data were smoothed using a fourth-order (0-lag) low-pass Butterworth filter with a cutoff frequency of 8 Hz. The takeoff flight time, as well as the average and maximum net force levels, were analyzed from the vertical ground reaction force signals separately for front and rear parts of the force plate. The takeoffs were videotaped (50 Hz) from the side through the window of the tunnel door. The mechanical 2-D model of the jumper consisted of eight segments (head, trunk, thigh, shank, foot, arm, forearm + hand), assuming that the action of both sides of the body was symmetrical, and the model was used mainly to characterize possible differences in movement patterns between the trials in different conditions. The 2-D coordinates of the joint centers were calculated from the manually digitized data, and the segment parameters were taken from the data of De Leva (1996; adapted from the Zatsiorsky–Seluyanov segment inertia parameters [Zatsiorsky et al., 1990]). The kinematic data were smoothed using a fourth-order (0-lag) low-pass Butterworth filter with a cutoff frequency of 8 Hz. The takeoff
time was determined between the first visible movement (start) and the end of the ground contact (toe-off) with the accuracy of the used video frame rate. Different joint (knee, hip) and segmental (shank, trunk) angles were calculated for the given start and toe-off instants. In the statistical analysis, the individual trials in different conditions with and without skis were compared by using two-tailed \( t \) test for samples with equal variances.

**Results**

A typical example of the ski jumping takeoff with skis in a wind tunnel is presented in Figure 2. Figure 3a shows the takeoff position of jumper A characterized by different joint and segmental angles at the initial takeoff position (start) and release instant (toe-off) in nonwind (0 \( \text{m} \cdot \text{s}^{-1} \)) and wind conditions (25 \( \text{m} \cdot \text{s}^{-1} \)) with skis. No significant differences were found in the start position whereas the toe-off position showed significant differences (e.g., 146.4–139.0° and 133.6–115.2° for the knee and hip angles in the nonwind and wind conditions, respectively). The behavior of the selected angular parameters during one typical takeoff with skis at the wind speed of 25 \( \text{m} \cdot \text{s}^{-1} \) is presented in Figure 3b. The decrease in takeoff time in the wind condition was 11 and 30% (\( p < .001 \)) without skis and 8 (\( p < .05 \)) and 14% (\( p < .001 \)) with skis for the jumpers A and B, respectively (Figure 4). The effect of the aerodynamic lift force is well demonstrated in Figure 5a as a reduction of vertical force during the initial takeoff position with skis in wind condition. Figure 5b shows the \( F_z \) force components under the rear and fore parts of the feet separately. The difference in the anteroposterior balance between the conditions with and without skis is seen as a change in the contribution of the rear and fore foot force components. Without skis, the force curves twice cross each other during the takeoff, whereas the first crossing in the beginning of the takeoff disappears with skis.

**Discussion**

As seen in Figure 2 (see also the video material) jumpers were able to perform very natural takeoff action (similar to the actual takeoff) with skis in the wind tunnel. According to the subjective feeling of the jumpers, the ski jumping takeoff with skis in the wind tunnel was even easier to perform than in the earlier trials without skis.

The small differences in the initial takeoff positions between the nonwind and wind conditions (Figure 3a) served as a good basis for the comparison of the takeoff times in different conditions. The smaller knee angle at the toe-off instant was found in the wind conditions, which certainly accounts at least partly for the time difference between the conditions. However, this time difference, corresponding to a difference of 7.4° in knee angle, is only about 10 ms, because of the very high maximum angular velocity of the knee joint at the release instant (\( > 14 \text{rad} \cdot \text{s}^{-1} \); Figure 3b). The more aerodynamic takeoff
position at the release instant in the wind conditions is clearly seen as a smaller upper-body (trunk) angle as compared with the nonwind conditions ($p < .001$).

The lower bodyweight during the initial phase of the take-off in the wind condition (Figure 5a) is most likely caused by the aerodynamic lift force. The force of horizontally moving air is being used to overcome the downward pull of gravity and therefore the lifting force is produced, as a jumper in the crouch inrun position acts like an airfoil. This lift may be advantageous at higher velocities, such as in speed skiing, as it reduces the ski friction. However, in ski jumping, the lift can be considered as a result from air resistance and therefore it very often indicates an unfavorable inrun position, in which the air goes under the upper body (Virmavirta et al., 2001).
It seems that skis did not much influence the total force levels produced (average and maximum forces) during the takeoff, but they still changed the anteroposterior force distribution under the feet (Figure 5b). The effect of skis in wind conditions is clearly seen in the contribution of the force components at the beginning of the takeoff. In the conditions without skis, the force components from the front and rear parts of the force plate are crossing twice during the takeoff, which indicates some unbalance in the anteroposterior direction. With the skis, the signals are crossing only once, which means that the contribution of the rear part of the feet is emphasized during the initial phase of the takeoff as the skis and ski bindings provide more support against the backward rotation of the body.

The contributions of the forces under the rear part of the feet are important probably because the strong dorsiflexion is needed for lifting the skis to the proper flight position. As explained in the introductory paragraphs, knees cannot be fully extended without plantar flexion and therefore these facts together with aerodynamic lift certainly explain most of the time difference in takeoff between the experimental conditions. The results presented in this fairly unique experiment emphasize that research on ski jumping takeoff can be advanced by using wind tunnels. Owing to high costs, the possibilities of wind tunnel measurements for ski jumping research are often very limited. The ideal situation would naturally be to obtain the measurements of the takeoff forces in actual jumping hill conditions. Nonetheless, whenever the recording of the force distribution under the feet is needed in a controlled situation, wind tunnel measurements with skis can be recommended.

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References