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The effect of wind on jumping distance in ski jumping depends on jumpers' aerodynamic characteristics

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ABSTRACT

Several studies have suggested re-evaluation of the wind compensation system (WCS) of the International Ski Federation (FIS). It was introduced in 2009, and since then, the system has been modified considerably, but major shortcomings have still remained. The present study compared the effect of tail/head wind on two reference jumps with different aerodynamic properties (C_d and C_l) during the flight phase. Jump distance and total tangential wind speed data of world cup competitions of the season 2020/2021 were used to analyse the FIS WCS and to offer basic information of wind effects. The correlation between the total tangential wind speed and the jump distance varied strongly among the analysed jumping rounds and showed a big variation in the effect of FIS WCS. According to the computer simulation, a steady head/tail wind during the entire flight phase did not show big difference in jump distance between the jumps with different aerodynamic properties. However, wind had a "reverse" effect on the jumps: when applied to the early flight phase, tail wind increased, and head wind decreased the jumping distance. It seems that the favourable wind conditions at the early flight phase may result in an unfair advantage-disadvantage when the current FIS WCS is used. Therefore, based on the present results, the FIS WCS needs to be further discussed and quality of jumpers' aerodynamic properties re-examined.

1. Introduction

The effect of wind on jumping distance in ski jumping was recognized long time ago, but the changing wind conditions were probably considered as part of the event, especially because it is very difficult to guarantee equal wind conditions for jumpers. Probably the most interesting example of the wind effects in ski jumping was witnessed when Poland's "*Wojciech Fortuna's surname turned out to be apt when he became Poland's first Winter Olympic Champion in 1972. Only selected for Sapporo at the last minute, Fortuna was a virtual unknown in the ski jumping world. His first jump in the large hill event, 111m, meant an overrun of the safety zone. Judges briefly discussed a re-arrangement of the starting position (and re-start of the competition), but Fortuna's result was allowed to stand. Wind severely influenced the event, and Fortuna's jump remained the longest of the first round. He struggled in the second jump with just 87.5m but retained the lead by a narrow 0.1 points. The Olympic gold remained his only significant career win" (*Olympedia, 2021*).*

Müller et al. (1996) published the first computer-based calculations of the effect of wind on jumping distance in ski jumping by concluding that "changes in the gust speed or direction will make every contest one of a gamble with the wind". After this clear evidence of wind effects, more attention was paid to solve the obvious fairness problem (see Müller, 2009). According to Müller (2009) one solution could be the correction of wind effects by means of computer simulation. First attempt was made in 2009, when the Fédération Internationale de Ski (FIS, International Ski Federation) introduced a new, easy-to-use wind compensation system (WCS), where the wind compensation factors were calculated according to the following formula (FIS Fact sheet, 2009):

$\Delta w = TWS * (HS - 36)/20$, where.

Δw = the wind effect on jumping distance in meters, TWS = the averaged tangential wind speed (m/s), and HS = the hill size (m). This was a very dramatic change in the nature of ski jumping because the longest jumps were not necessarily the best ones anymore.

The FIS WCS has remained same with fixed compensation factors including some minor adjustments, e.g., 21% increase in tail wind effect and weighting the values of the wind anemometers in different locations along the landing slope. The current weighting percentages of seven anemometers (A1-A7) used in the large hill (anemometer positions from

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the critical point (K) are 10 % K, 30 % K, 45 % K, 60 % K, 75 % K, 90 % K and 105 % K) are 10% (A1), 10% (A2), 20% (A3), 20% (A4), 15% (A5), 15% (A6) and 10% (A7). The linear compensation factors are appropriate only for a limited range of jumping distances (calculated for the “winner's distance, Gasser, 2018) and it is very difficult to solve the problem when jumpers' performance level differ a lot in the same competition. Fig. 1 shows the linearity problem of the fixed compensation factor by comparing it with the computer-simulated jumps in different wind conditions. The difference between the curves is mainly caused by the ski jumping hill profile: wind has the greatest effect on the jumps landing on the zone where the gradient of the landing slope is steepest (Virmavirta and Kivekäs, 2012). Fixed factors are usually determined to work for the jumping distances in the middle of the critical (K) and hill size (HS) points of the jumping hill. Fig. 1 also shows that the adjustment of 21% for the tail wind effect, mentioned above, improved the FIS WCS (the detailed decription on the used computer simulation is presented in the methods section).

All the past studies of wind effects on jumping distance in ski jumping have shown that headwind increases, and tail wind decreases jump distance (e.g., Virmavirta and Kivekäs, 2012). However, Jung et al. (2018) found recently “a reverse” wind effect in favourable wind conditions. They mentioned that this “reverse” wind effect, where jump length increases due to tail wind and decreases due to head wind in the first part of the flight, was more pronounced with increased drag areas and it depends on the direction of the airflow in the sagittal plane. Virmavirta and Kivekäs (2019) also found this “reverse” effect when they changed the aerodynamic profile of the reference jump, which they had used earlier (e.g., Virmavirta and Kivekäs 2012). They mentioned that the “reverse” wind effect seems to be dependent on ski jumpers' aerodynamic characteristics during the flight phase and therefore, suggested the same as Jung et al. (2018): a new revision of the FIS WCS. Reevaluation of the FIS WCS has been suggested by Aldrin (2015) and Pietschnig et al. (2020) as well. The “reversed” wind effect was recognized also by FIS as they recently (2019, see Appendix) changed the tangential wind reading of the first anemometer ($v_{w1,}$ located at 10% of the K point) according to the following calculation:

$$v_{w1} = \begin{cases} v_{w1} + 2, v_{w1} < -1m/s \\ -v_{w1}, v_{w1} \geq -1m/s \end{cases}$$

This means that if the tangential wind (− tail wind, + head wind) in the first anemometer is <−1 m/s, the value will be added by +2 m/s or if the wind is ≥−1 m/s, the sign of the value is reversed. With this correction, for example, tail wind −2 m/s in the first anemometer becomes 0 m/s.

Based on the above-mentioned inaccuracies in the FIS WCS Jung et al. (2021) introduced an alternative mathematical, mechanistic model-based wind compensation approach. This mathematical wind compensation offers the opportunity to react to wind in every single ski jump and the accuracy of the estimated jump length effect of this approach depends only on the measurement errors in the kinematic and wind velocity data. Therefore, to solve the problems in the wind compensation system, jumpers' current aerodynamic properties (C_dA and C_lA) should be known and the measured wind values along the flight path should be accurate. This would probably mean more wind anemometers in both sides of the landing slope mounted at the height of the glide path every 5–10 m (Müller, 2009). Inertial measurement units (IMUs) combined with the ultra-wide band technology (UWB) can collect the necessary data of flight acceleration, flight velocity, and flight path coordinates (already used by the FIS in practice) (Jung et al., 2021). The situation is very complicated if some jumpers will benefit from the wind and others will not as shown by Virmavirta and Kivekäs (2019). As the “reverse” wind effect has been found to be more pronounced with increased drag areas in the first part of the flight, the purpose of the present study was to find out how wind affects the jumps with different aerodynamic characteristics (drag and lift values, C_d, C_l). Therefore, two jumps with different aerodynamics were compared. Following the approach of Jung et al. (2021), also jump distance and total tangential wind speed data of world cup competitions of the season 2020/ 2021 were used to analyse the FIS WCS and to offer basic information of wind effects.

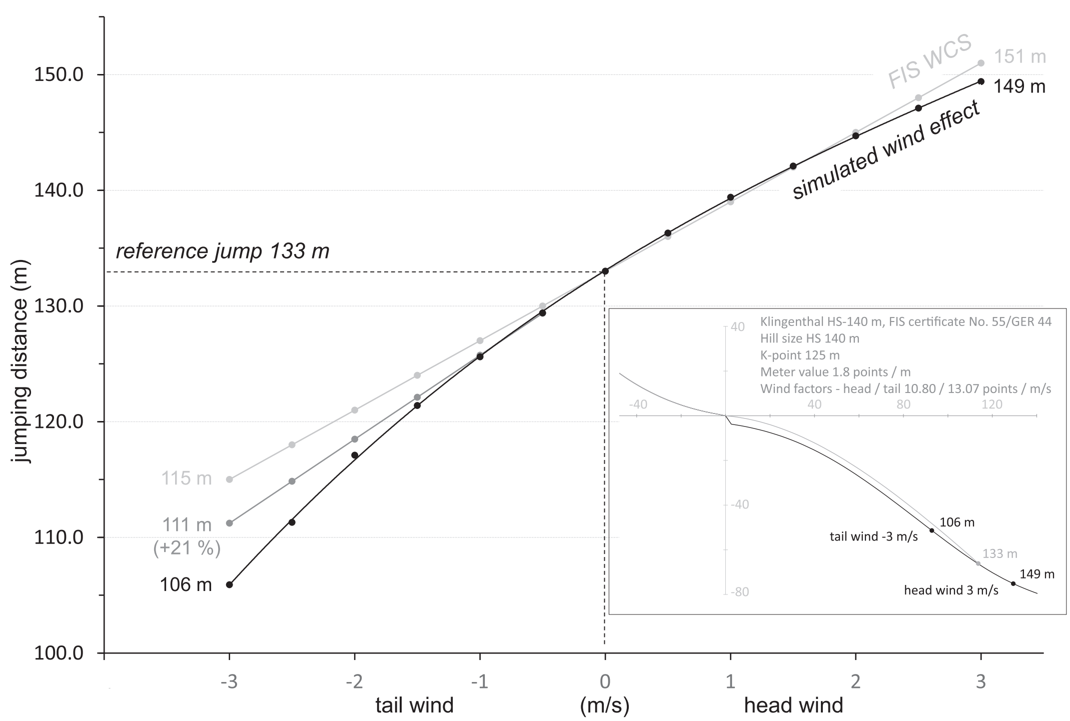


Fig. 1. Comparison between the jumps compensated by the FIS WCS with a fixed wind factors (6.00 and 7.26 m/1 m/s for head and tail wind, respectively) and the computer-simulated jumps in different wind conditions. The increased effect of tail wind by 21% in FIS WCS is shown separately. The embedded graph shows the flight trajectory of the simulated reference jump (133 m) in non-wind conditions.

2. Methods

2.1. The correlation between jump distance and total tangential wind speed

The correlation between jump distance and total tangential wind speed (both given in the official FIS result documents) was analysed from the selected world cup competitions of the season 2020–2021 including different wind conditions and athletes with different performance level. It is known that the inrun velocity parallel to the take-off table is a major jump distance determinant in ski jumping and therefore, only jumps from the same starting gate were included. This does not necessarily remove completely the effect of speed on jumping distance since there are other factors (e.g. body weight) affecting speed as well, but the selected correlation data in the present study did not show any significant correlation between the inrun speed and jumping distance. The Pearson correlation coefficients between the uncompensated (given in the official FIS result documents) and compensated jump distance and the tangential wind speed were used to estimate the FIS WCS accuracy. The correlation is supposed to decrease after the application of wind compensation which is based on the FIS hill-specific parameters.

2.2. Reference jumps with different aerodynamic characteristics

The effect of wind on jumping distance (133 m) of two reference jumps (A and B) with different aerodynamic properties was analysed by a computer simulation. Jump B had higher drag values at the early flight phase and higher lift values at a later phase of the flight. All the other input parameters were same. Analysis used a model of the complete ski jump (ski jumper is considered as point mass): the inrun, take-off and flight according to Virmavirta and Kivekäs (2012). The following parameters were used as input information: total mass and reference area of a ski jumper (based on jumper's anthropometrics) including skis, air density, coefficient of ski friction, take-off force profile, drag (C_d) and lift (C_l) coefficients for the crouch inrun position, and C_d(t) and C_l(t) for the flight phase (Fig. 2). The lift/drag diagrams for reference jumps A and B are based on several field studies and wind tunnel experiments carried out with ski jumpers and doll models (Virmavirta and Kivekäs, 2012; Jung et al., 2018, respectively). The hill profile used in the present study was the large hill annually used in the FIS World Cup competitions (Klingenthal HS-140m, FIS certificate No. 55/GER 44).

2.3. Wind scenarios

Steady tangential wind was applied to the entire flight phase (head wind +2.0 → tail wind −2.0 m/s, Table 1), and separately to the early flight phase only until the end of the "reverse" wind effect was found at the "turnover" point (Jung et al., 2018, 2021). Wind was also applied separately in 10% intervals to the reference jump of 133 m. This scenario shows the effect of wind in different phases of the jump. Additional wind scenarios were applied in which a slight tangential head/tail wind was added at end of the flight phase for the reference jump B. As an example, the wind values of −3 m/s at 0–20 m and −0.5 m/s from 100 m to landing were applied to test the FIS WCS and to get a weighted

Table 1
The effect of head (+) and tail (−) wind on jumping distance of two reference jumps A and B (both 133 m), applied separately for the entire and early flight phase. The "turnover" (Jung et al., 2018) shows the distance from the take-off edge, where the "reverse" wind effect ends for the jump B. After this point headwind increases, and tail wind decreases the jump distance also for jump B.

Wind(m/s)	Entire flight		Early flight phase		"turnover"
	A (m)	B (m)	A (m)	B (m)	B (m)
+2.0	144.7	144.8	134.9	133.0	33.2
+1.5	142.1	142.2			
+1.0	139.4	139.4	134.0	133.0	33.4
+0.5	136.3	136.4			
0.0	133.0	133.0	133.0	133.0	
−0.5	129.4	129.3			
−1.0	125.6	125.3	131.9	133.0	31.0
−1.5	121.4	120.9			
−2.0	117.1	116.3	130.8	133.0	31.1

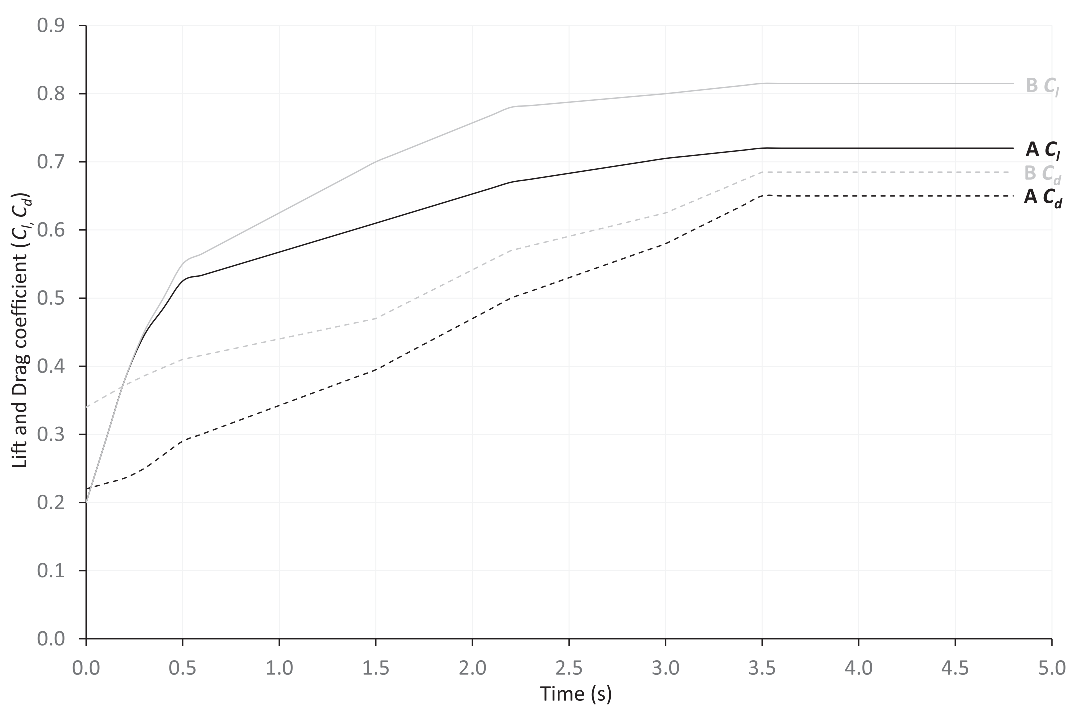


Fig. 2. Aerodynamic lift (C_l, solid lines) and drag (C_d, dashed lines) coefficients of the flight phase for two different reference jumps (A and B) of same jump distance (133 m, total flight time 4.8 s) in non-wind conditions. The references Virmavirta and Kivekäs (2012) and Jung et al. (2018) were utilized for the jumps A and B, respectively.

tangential wind speed from 7 anemometer readings along the landing slope.

3. Results

3.1. The effect of the FIS wind compensation system analysed from the world cup data

The correlation between the total tangential wind speed and the jump distance varied strongly among the analysed jumping rounds (Fig. 3a-h). Fig. 3 shows also a big variation in the effect of FIS WCS. Strongest correlations were found in the second competition round on the HS − 142 m hill in Titisee-Neustadt and on the HS − 97 m hill in Rasnov ($r = 0.721$, $p = 0.000$; $n = 30$ and $r = 0.695$, $p = 0.000$; $n = 28$, respectively). These correlations decreased slightly but remained significant after compensation ($r = 0.553$, $p = 0.002$ and $r = 0.475$, $p = 0.011$). The example from ski flying (Planica HS − 240, 1st round, $n = 35$) did not show any significant correlation before or after compensation. In Zakopane HS − 140 m hill the good jumpers, who qualified to the second round, showed strong correlation ($r = 0.639$, $p = 0.000$, $n =$

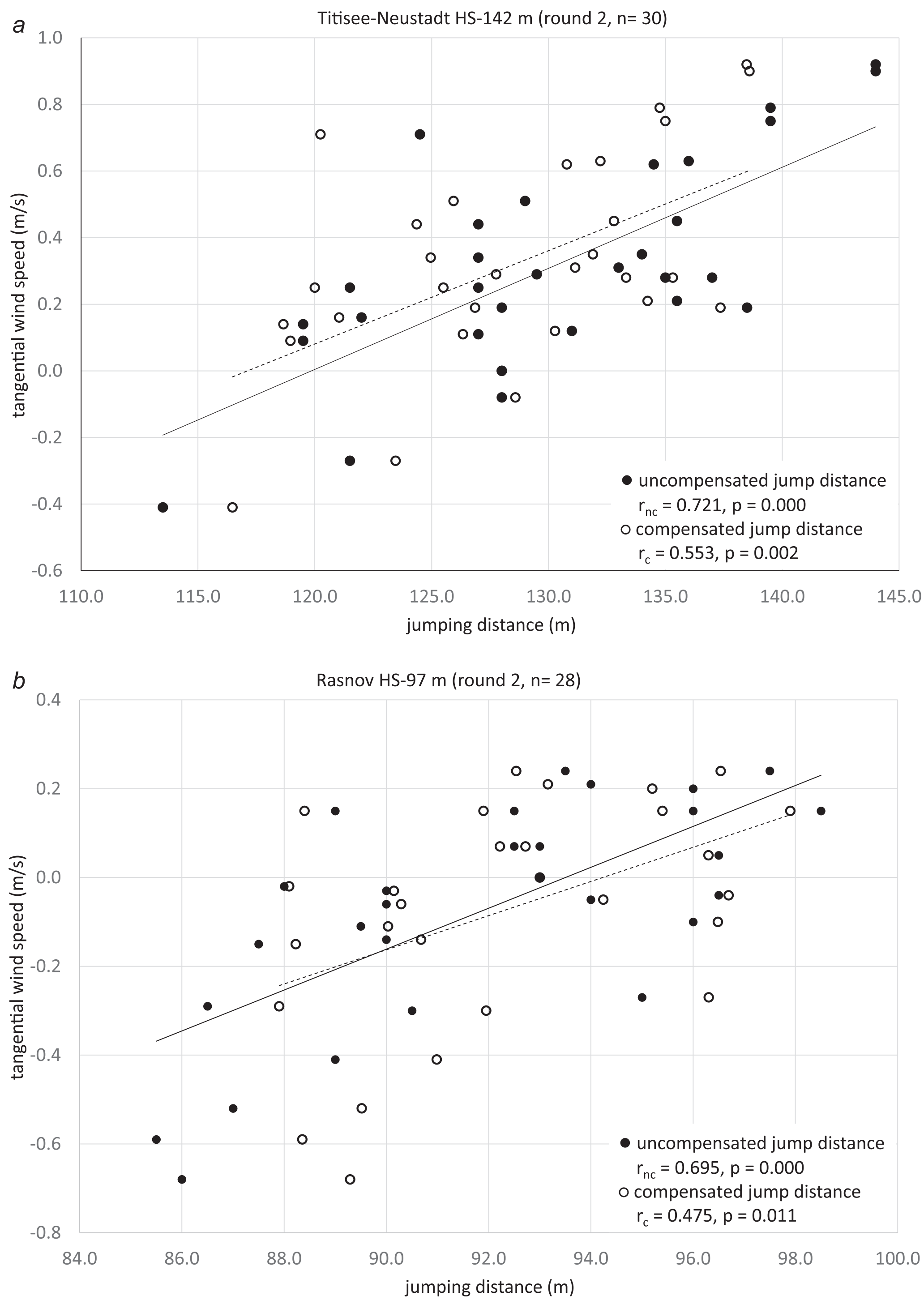
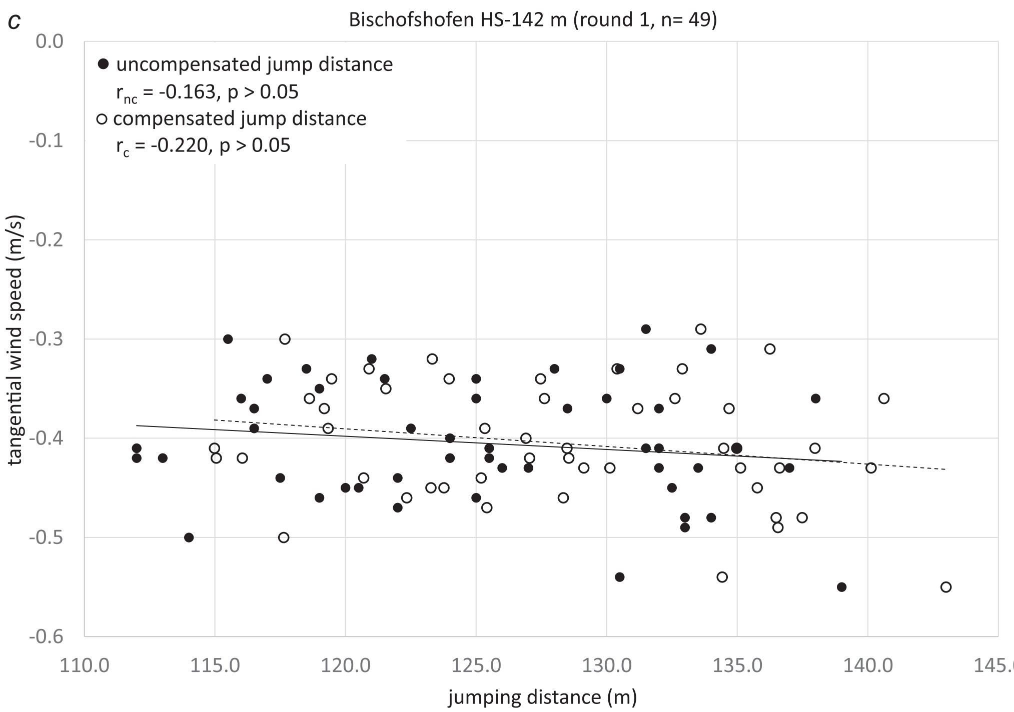


Fig. 3. Total tangential wind speed and uncompensated and compensated jump distances of selected world cup competitions. Filled circles (●) with solid correlation trendlines (—) correspond to uncompensated jump distances and open circles (○) with dashed trendlines (–) correspond to compensated distances.



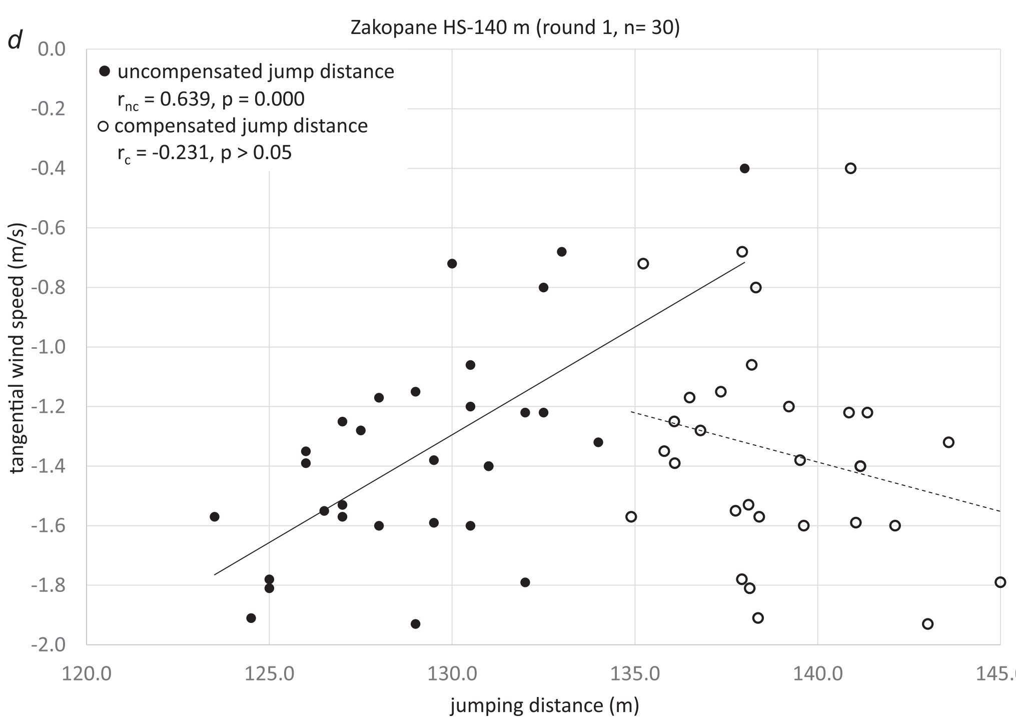


Fig. 3. (*continued*).

30). However, this correlation turned negative after compensation ($r = -0.231$, $p > 0.05$). In the 2nd round same jumpers showed strong correlation again ($r = 0.594$, $p = 0.001$), and after compensation this correlation decreased ($r = 0.323$, $p = 0.082$). Another interesting correlation was found on the HS – 137 m hill in Oberstdorf where strong negative correlation was found after the FIS WCS ($r = -0.337$, $p = 0.008$, $n = 61$).

3.2. The effect of wind on reference jumps with different aerodynamic characteristics

A steady head/tail wind during the entire flight phase did not show big difference in jump distance between the jumps A and B (Table 1). However, the head or tail wind only in the early flight phase (up to 31 m in tail wind and 33 m in head wind) showed the “reverse” effect (slightly increased jump distance in tail wind and decreased jump distance in head wind until the “turnover” point) for B, whereas A showed the opposite results. This “reverse” wind effect in the early flight phase can also be seen until “turnover” point in Fig. 4 where head and tail wind (1 and 2 m/s) were applied separately to the different phases of the reference jump B (133 m) with 10% intervals in jump distance (e.g. 0–10%, 10–20% etc.). The given additional example (see 2.3.) for tail wind (−3 m/s early flight and −0.5 m/s end flight) corresponds to −0.225 m/s of weighted tangential wind speed and +2.94 points (1.63

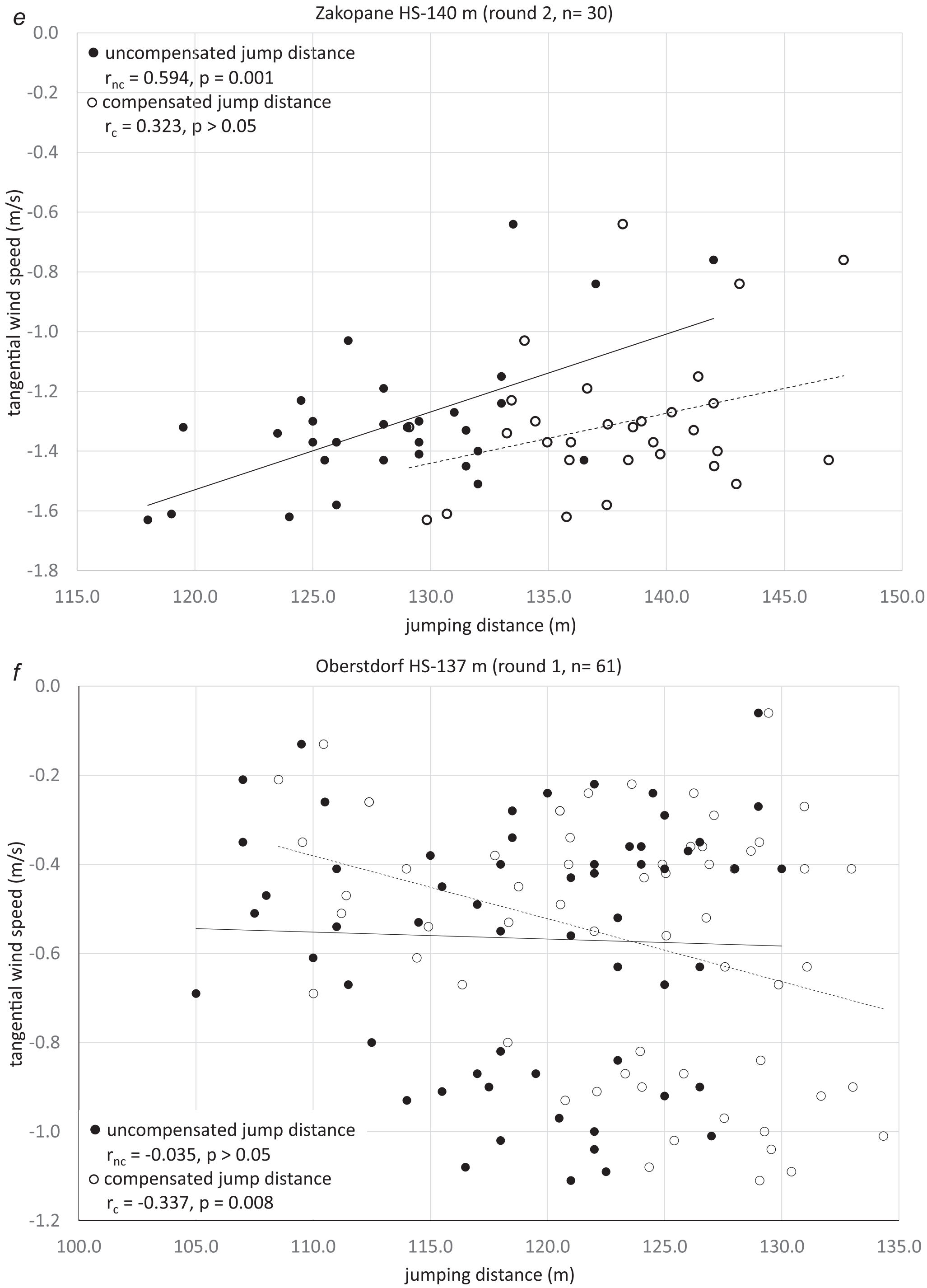


Fig. 3. (*continued*).

m) according to FIS hill-specific factor (1 m/s tail wind = +13.07 points, Fig. 1). The simulated jumping distance was 133.4 m for this example jump.

4. Discussion

A huge effect of wind on the jumping distance in ski jumping is well recognised, but a solution to the fairness problem, i.e., guarantee of equal wind conditions for all jumpers, seems unattainable. Jung et al. (2021) mentioned that “wind is a chaotic phenomenon and changes arbitrarily; consequently, fairness is never guaranteed“, and therefore, attempts to compensate the wind effects most likely lead to a new fairness problem. This problem arises, at least, from three different sources. One is the fact that wind has the greatest effect on short jumps landing on the zone where the gradient of the landing slope is steepest (Virmavirta and Kivekäs, 2012). Then the final result is very much dependent on the jump distance used as a basis for the hill specific factors of WCS. The second one is the accuracy of the “estimated” average tangential wind speed provided by the wind anemometers along the flight path. This is very important especially in changing wind conditions, when the anemometer readings differ from each other during one jump, and the final compensation points exceed the difference between the points of winning and losing the competition. The results of this study show the third source of fairness problem as the effects of

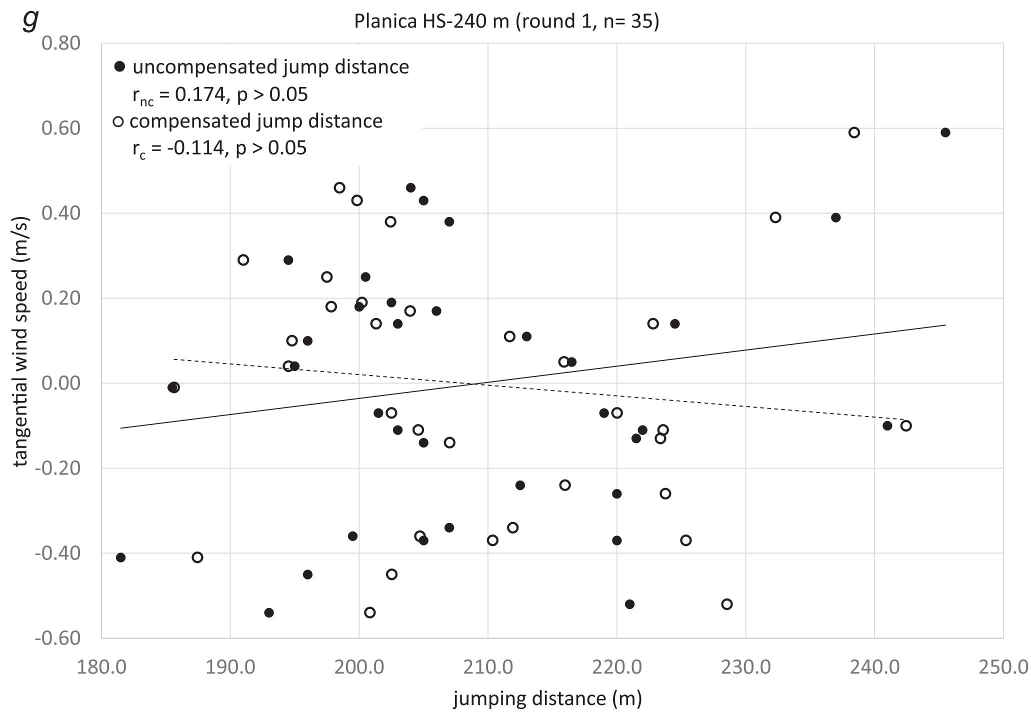


Fig. 3. (*continued*).

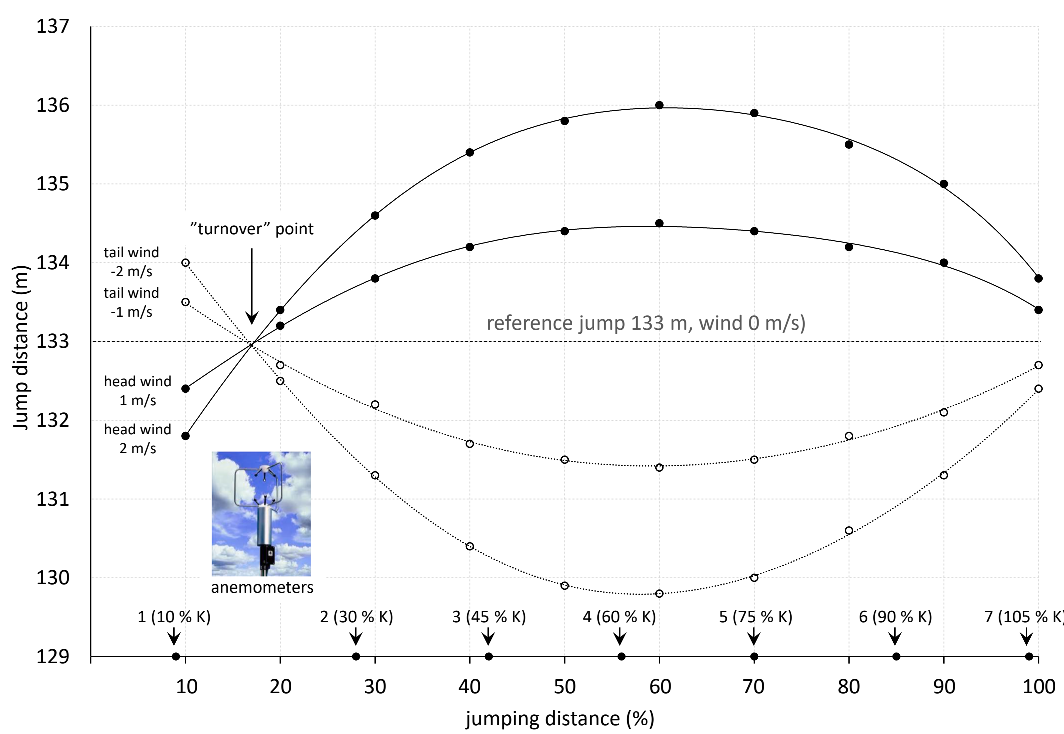


Fig. 4. Head and tail wind (1 and 2 m/s) applied to the different phases of the reference jump B (133 m) with 10% intervals in jump distance (0–10%, 10–20% etc.). Location of the FIS wind anemometers is presented in the x-axis (K-point = 125 m). The "reverse" wind effect can be seen in the early flight phase.

wind depend strongly on jumpers' aerodynamic lift and drag characteristics at the early flight phase, which makes the compensation system very questionable.

The *correlation analysis* between the total tangential wind speed and the jump distance showed strong variation both in the uncompensated and compensated results, which is in line with previous analyses for the competition season 2019–2020 (Jung et al., 2021). It is obvious that good jumpers are able to take advantage of good wind conditions and can handle bad conditions better than less skillful jumpers and therefore, the correlation does not necessarily show up. However, the strong correlation was found in the second round of Titisee-Neustadt (HS-142 m, n = 30 and Rasnov HS-97 m, n = 28), but the correlation did not change much after the compensation. Although the strong variation makes it difficult to interpret the correlation examples presented in Fig. 3, usefulness of the wind compensation is obviously much dependent on strength and direction of wind. Bischofshofen is an example, where the range of wind speed for all jumpers was very small (−0.29 to −0.55 m/s), and the compensation did not change the final result much, whereas in Zakopane, the range of wind speed was larger (−0.40 to −1.93 m/s), and the compensation changed the results. For example, the tail wind of −1.93 m/s corresponded to the compensation points of +25.2 points (14 m in jumping distance, 129 → 143 m, and ranking of the jumper 15. → 3.). In this competition round, the difference between the jumpers in the first and second place was only 2.6 points, which certainly raises the question of whether there is a real winner on the podium in a competition, where the differences are small. Strong variations in correlation analysis before and after the wind compensation can be due to the large influence of other jump distance determinants and/or due to inaccuracies associated with the determination of tangential wind speed (Jung et al., 2021).

It seems that the different wind effect on jumps A and B (Table 1) is much dependent on *jumpers' aerodynamic properties* (Fig. 2) during the flight phase. As seen in Table 1, the effect of steady wind during the entire flight phase did not differ between the jumps A and B. However, when wind was applied to the early flight phase only, the effects were different: head wind increased/decreased and tail wind decreased/increased the jumping distance of the jumps A/B, respectively. This "reverse" wind effect was first found by Jung et al. (2018). The "reverse" wind effect on jump B can be explained mostly by higher drag values at the early flight phase (Jung et al., 2018) (Fig. 2). Direction of the airflow in sagittal plane was not changed in the present study, but Jung et al. (2018) found that largest "reverse" wind effects occurred, when wind blew closer to horizontal (20° from tangential to landing slope 0°). The present study suggests that wind may have a twofold effect at the early flight phase: it may be an advantage or a disadvantageous depending on jumpers' aerodynamic properties. Thus, it would be important to know the current aerodynamic C_dA and C_lA values and update them whenever any changes in equipment (skis and suit) has been done. According to Jung et al. (2018), the "reverse" wind effect was more pronounced with increased drag areas. This could mean that the athletes with larger body size may benefit or not, depending on the wind direction (head or tail wind), from WCS due to the "reverse" wind effect.

The additional wind scenario, although fairly theoretical, presents an "unfair advantage" of 2.94 points for the jump B (133 m). This means that under favourable wind conditions, a jumper can get a bonus by the FIS WCS, although the simulated jump distance was not negatively affected by wind (133.4 m). It is obvious that the hill specific factors of FIS WCS are based on computer simulations, but there is no well documented information on how the parameters were determined (Gasser, 2018). In their recent studies Jung et al. (2018) reduced drag areas of reference jumps by a factor of 0.9 due to today's smaller/tighter jumping suits. The authors also showed interest to measure athletes in their current equipment in wind tunnel for a future project. In 2021, Jung et al. introduced a new mechanistic model-based WCS, in which aerodynamic coefficients of the real ski jump could be obtained from kinematic and wind velocity data collected during the flight. The accuracy of this system was considered to depend only on the measurement errors in the kinematic and wind velocity data. Since ski jumpers' flight position can change and wind gusts occur suddenly and locally, it is been considered reasonable to collect the data at least every 10 m along the landing slope starting from the edge of the take-off table (Jung et al., 2021). This is much more than the current time-averaged tangential wind speed data from seven anemometers (large hill) used as input for a linear model of FIS WCS. Adding the number of wind anemometers at both sides of the landing slope, and comparing them with the wind values at jumper's flight path, would certainly improve the accuracy of the current system.

The above mentioned complex compensation system raises the question of whether everything should be able to be compensated in ski jumping. Based on the present data, it can also be thought that the result caused by the wind is correct, although not necessarily fair, while the compensated results always include uncertainties. It is already now fairly difficult for spectators to follow and estimate athlete's performance without wind compensation points which can be unpredictable. Adding the number of jumps in the final result of one single competition, as suggested by e.g. Jung et al. (2021), would certainly decrease the need for compensation. It can be *concluded* that the "reverse" wind effect found in the present study seems to be dependent on ski jumpers' aerodynamic characteristics during the flight phase. Therefore, based on the present results and the earlier studies (Aldrin, 2015; Pietschnig et al., 2020; Jung et al., 2018, 2021) the FIS WCS needs to be further discussed and quality of jumpers' current aerodynamic properties re-examined.

CRediT authorship contribution statement

Virmavirta Mikko: . **Kivekäs Juha:** Writing – review & editing, Validation, Supervision, Software, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2022.111101.

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