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A heuristic model-based approach for compensating wind effects in ski jumping

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ABSTRACT

Wind influences the jump length in ski jumping, which raises questions about the fairness. To counteract the wind problem, the International Ski Federation has introduced a wind compensation system in 2009: time-averaged wind velocity components tangential to the landing slope are obtained from several sites along the landing slope, and these data are used in a linear statistical model for estimating the jump length effect of wind. This is considered in the total score of the ski jump. However, it has been shown that the jump length effect estimates can be inaccurate and misleading. The present article introduces an alternative mathematical wind compensation approach that is based on an accurate mechanistic model of the flight phase. This estimates the jump length effect as difference between the jump length of the real ski jump at the given wind condition and the computed jump length of the simulated ski jump at calm wind. Inputs for the computer simulation are the initial flight velocity and aerodynamic coefficients of the real ski jump that can be obtained from kinematic and wind velocity data collected during the flight. The initial flight velocity is readily available from the kinematic data and inverse dynamics can be used to compute the aerodynamic coefficients. The accuracy of the estimated jump length effect of the mechanistic model-based approach depends only on the measurement errors in the kinematic and wind velocity data, but not on inaccuracies of an approach that is based on a linear statistical model.

1. Introduction

The length of a ski jump is determined by the in-run velocity parallel to the ramp, the take-off velocity perpendicular to the ramp, and the forces that act during the flight on the athlete with his equipment, namely the gravitational force, and the aerodynamic forces drag and lift (Straumann, 1927; König, 1952; Denoth et al., 1987; Müller et al., 1995; Müller et al., 1996). Drag and lift depend on the air density, the airflow velocity, and the flight position (Fig. 1a) that can be controlled by the athlete. The goal is to optimise the flight position time course (flight technique) within the admissible range such that the generated aerodynamic forces maximise the jump length. The admissible range is constrained by the requirement of a balanced pitching moment to avoid tumbling and by the athlete's individual features and abilities. Mechanistic modelling can be used to understand the constrained optimisation problem of the flight phase that the athlete has to solve within a few seconds (Jung et al., 2014; Jung et al., 2019).

Since ski jumping is an open air sport, the athletes are exposed to wind. Wind changes the airflow velocity and thus the aerodynamic forces. Consequently, the jump length is not only determined by the athlete's performance but also by the given wind condition. This raises fairness questions in competitions. To counteract the wind problem, the International Ski Federation (FIS) has introduced a wind compensation system (WCS) in 2009 (FIS, 2009). The FIS WCS estimates the jump length effect of wind by a linear statistical model that uses time-averaged wind velocity components tangentially to the landing slope (tangential wind speeds) as inputs. This jump length effect is considered in the total score of a ski jump with the consequence that the longest jump is not necessarily the best one. Until 2014, the FIS WCS has been modified considerably to capture the effect of wind on the jump length in more detail (FIS, 2016). However, analyses based on data of elite competitions (Aldrin, 2015; Pietschnig et al., 2020) showed that the estimated jump length effects can still be inaccurate. This indicates that major shortcomings have remained.

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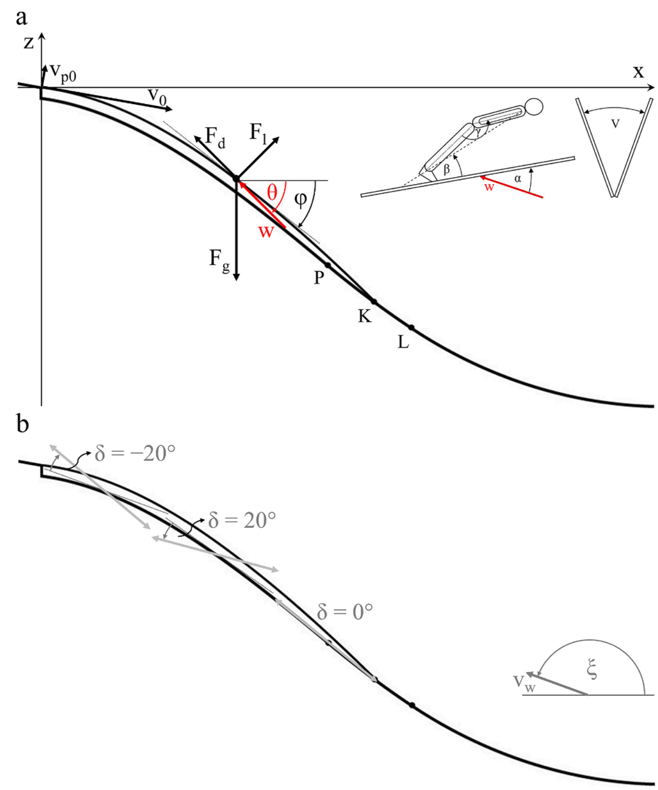

Fig. 1. (**a**) Schematic drawing of the flight path, the landing slope in the vertical *x-z* plane, and the flight position angles. The flight path of the athlete with equipment is determined by the initial mass centre flight velocity that results from the in-run velocity parallel to the ramp $\mathbf{v}_0$ and the take-off velocity perpendicular to the ramp $\mathbf{v}_{p0}$, and by three forces: gravitational force $\mathbf{F}_g$, and aerodynamic forces drag $\mathbf{F}_d$ and lift $\mathbf{F}_l$. Drag and lift are functions of the flight position and this is characterised by four angles: angle of attack of the skis α relative to the airflow **w**, body-to-ski angle β, hip angle γ, *V*-angle of the skis to each other. The flight path angle is denoted by φ and θ is the airflow angle. They are measured with respect to the horizontal. The landing slope profile is modelled according to the parameters given in the FIS Certificate of Jumping Hill. The hill size (HS) length is defined to be the length between the ramp edge and the L-point along the landing slope. (**b**) Schematic drawing of the wind velocity $\mathbf{v}_w$ in the vertical *x-z* plane. The wind angle relative to the horizontal line ξ is counted positive in counter-clockwise direction and δ is the deviation of the wind direction from the tangent of the landing slope. Thus, δ is 0° when wind blows tangentially to the landing slope and the deviations $\delta = +20°$ and $-20°$ were also considered.

The development of an accurate wind compensation system is difficult because numerous factors determine the jump length effect: wind speed and direction, phase of the flight in which wind occurs, performance of the athlete with given equipment, and both the hill size and the landing slope profile (Müller et al., 1996; Schmölzer and Müller, 2002; Virmavirta and Kivekäs, 2012; Jung et al., 2018; Virmavirta and Kivekäs, 2019). For wind components in the vertical plane, Jung et al. (2018) have recently published a mechanistic model of the flight phase that accounts for all these factors. This is used here as basis for developing a heuristic model-based approach for accurate compensation of wind effects on the jump length (mechanistic model-based WCS). The present article starts with an analysis of the existing statistical model-based FIS WCS. The first part of the analysis is based on data of world cup competitions of the season 2019/2020, and the second part is based on data of simulated ski jumps in several realistic wind scenarios. The same computer simulation data is then used to analyse the mechanistic model-based WCS. This is followed by a comparison of both mathematical wind compensation approach, and advantages and disadvantages are discussed.

2. Methods

2.1. Mechanistic model of the flight phase

The athlete with equipment is idealised as a point mass and the flight path is considered to be in the vertical *x-z* plane (Fig. 1a). Initial conditions for the flight path are the initial flight velocity and the initial coordinates of the mass centre. The initial flight velocity results from the in-run velocity parallel to the ramp $\mathbf{v}_0$ and the take-off velocity perpendicular to the ramp $\mathbf{v}_{p0}$. After the athlete has left the ramp, the flight path is determined by the gravitational force $\mathbf{F}_g = m\mathbf{g}$ and the aerodynamic forces drag $\mathbf{F}_d = (\rho/2)D\mathbf{w}^2$ and lift $\mathbf{F}_l = (\rho/2)L\mathbf{w}^2$ (Fig. 1a). The gravitational force $\mathbf{F}_g$ depends on the mass m of the athlete with equipment and the gravitational acceleration **g**. Drag $\mathbf{F}_d$ and lift $\mathbf{F}_l$ depend on the air density ρ, the airflow velocity **w**, and the drag area D and lift area L, respectively. Drag area $D = c_D A$ and lift area $L = c_L A$ are functions of the flight position with given equipment (Fig. 1a), A is the cross-sectional area of the athlete with equipment, and c_D and c_L are the drag and lift coefficients, respectively. Wind changes the airflow velocity: $\mathbf{w} = \mathbf{v}_w - \mathbf{v}$, $\mathbf{v}_w$ is the wind velocity and **v** is the flight velocity of the mass centre (tangentially to the flight path).

The motion of the athlete with equipment can be described by a coupled system of four ordinary differential equations (Jung et al., 2018):

$$\dot{\mathbf{s}}(t) = \begin{bmatrix} \dot{v}_x(t) \\ \dot{v}_z(t) \\ \dot{x}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} \dfrac{-F_d(t)\cos\theta(t) - F_l(t)\sin\theta(t)}{m} \\ \dfrac{-F_d(t)\sin\theta(t) + F_l(t)\cos\theta(t)}{m} - g \\ v_x(t) \\ v_z(t) \end{bmatrix} \tag{1}$$

with initial conditions

$$\mathbf{s}(t_0) = (v_x(t_0), v_z(t_0), x(t_0), z(t_0))^T$$

$$\mathbf{v}(t_0) = \mathbf{v}_0 + \mathbf{v}_{p0}$$

$$x(t_0) = z(t_0) = 0 \tag{2}$$

The state matrix of the equation system is **s**, and θ is the airflow angle (Fig. 1a). To simulate a ski jump on a given hill, this initial value problem is solved with respect to the landing slope profile $p_{ls} : z(x)$. The simulated flight path intersects the landing slope at the final flight time t_f and the corresponding flight path coordinate $x(t_f)$ at landing is used for computing the jump length l along the landing slope surface starting from the ramp edge. The MATLAB® ordinary differential equation solver *ode45* (MATLAB® Release 2019a, MathWorks, USA) was used to apply the Dormand-Prince adaptive stepsize method for solving. The maximum time step was set to 0.1 s and the corresponding discretisation error was below 0.1 m.

2.2. Wind compensation systems

2.2.1. FIS wind compensation system

The FIS WCS estimates the jump length effect of wind (Δl_{FISWCS}) based on a linear statistical model that uses time-averaged tangential wind speeds as inputs. The tangential wind speed is measured with anemometers at several sites (e.g. seven on a large hill) along the landing slope in the approximate height of the flight path and data are collected and averaged over a predefined measurement time. To take into account that the jump length effect depends on the phase of the flight in which wind occurs, the tangential wind speed measured at the first anemometer is mathematically processed and then, all tangential wind speeds are weighted with site-specific parameters and summed up to get the total tangential wind speed. Mathematical processing of the tangential wind speed at the first anemometer is done to consider that head- and tailwind in the initial flight phase can have the opposite effect on the jump length than in the remainder of the flight (Jung et al., 2018; Virmavirta and Kivekäs, 2019). To take into account that the jump length effect depends on the hill size, the tangential wind speeds are finally weighted with a hill-specific parameter to obtain the estimated jump length effect. The hill-specific parameter is multiplied by 1.21 if the total tangential wind speed is negative to consider that negative jump length effects can be larger than positive jump length effects due to the nonlinear landing slope profile (Virmavirta and Kivekäs, 2012). Information on how the parameters were determined have not been published. The FIS WCS is described in detail in Appendix 1.

2.2.2. Mechanistic model-based wind compensation system

The mechanistic model-based WCS estimates the jump length effect (Δl_{MBWCS}) as the difference between the measured jump length of the real ski jump at given wind conditions and the computed jump length of the simulated ski jump at calm wind. The computer simulation is based on the presented mechanistic model (1)-(2). Inputs are the initial flight velocity $\mathbf{v}(t_0)$ and aerodynamic coefficients $k_D(t)$ and $k_L(t)$ of the real ski jump. These can be obtained from the flight acceleration $\dot{\mathbf{v}}(t)$ and velocity $\mathbf{v}(t)$ (kinematic data), and wind velocity $\mathbf{v}_w(t)$ (wind velocity data) collected during the flight. The initial flight velocity is readily available from the kinematic data collected at the start of the flight and the aerodynamic coefficients can be computed using inverse dynamics based on the kinematic and wind velocity data collected during the entire flight. To avoid measurements of the air density and the mass of the athlete with equipment, the aerodynamic coefficients are defined as $k_D = [\rho/(2m)]D$ and $k_L = [\rho/(2m)]L$ and (1) is rewritten accordingly to obtain

$$\dot{\mathbf{s}}(t) = \begin{bmatrix} \dot{v}_x(t) \\ \dot{v}_z(t) \\ \dot{x}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} -k_D(t)w(t)^2\cos\theta(t) - k_L(t)w(t)^2\sin\theta(t) \\ -k_D(t)w(t)^2\sin\theta(t) + k_L(t)w(t)^2\cos\theta(t) - g \\ v_x(t) \\ v_z(t) \end{bmatrix} \tag{3}$$

where $w = |\mathbf{w}|$ is the airflow speed. Through conversions of the rewritten equation system, the aerodynamic coefficients can be expressed as functions of the x- and z-components of the flight acceleration $\dot{\mathbf{v}}$, the flight velocity $\mathbf{v}$, and the wind velocity $\mathbf{v}_w$:

$$k_D(t) = \frac{-\dot{v}_x(t)\cot\theta(t) - \dot{v}_z(t) - g}{w(t)^2\cos\theta(t)\cot\theta(t) + w(t)^2\sin\theta(t)} \tag{4}$$

and

$$k_L(t) = \frac{-\dot{v}_x(t)\tan\theta(t) + \dot{v}_z(t) + g}{w(t)^2\sin\theta(t)\tan\theta(t) + w(t)^2\cos\theta(t)} \tag{5}$$

with $w = \left|\begin{pmatrix} w_x \\ w_z \end{pmatrix}\right| = \left|\begin{pmatrix} v_{w_x} \\ v_{w_z} \end{pmatrix} - \begin{pmatrix} v_x \\ v_z \end{pmatrix}\right|$ and $\theta = \text{atan}(w_z/w_x)$.

The estimation accuracy of the mechanistic model-based WCS depends on the simulation accuracy. For wind components in the vertical plane, the simulation accuracy depends on the spatial resolution of the computed aerodynamic coefficients, and on the measurement errors in the kinematic and wind velocity data. Aerodynamic coefficients can only be computed at those points in flight where kinematic and wind velocity data are simultaneously available. Elite athletes can change their flight position within fractions of a second and wind gusts can occur suddenly and locally. It is therefore considered reasonable to compute the aerodynamic coefficients at least every 10 m along the landing slope starting from the ramp edge. Elite athletes usually land between the K-point and the L-point (Fig. 1a) and consequently, the aerodynamic coefficients should be computed until the L-point. For a HS 140 m large hill with L-point at 140 m using a 10 m spacing, up to 15 aerodynamic coefficient pairs (k_D and k_L) are then computed. If the real ski jump ends before the L-point, the set becomes smaller since only the wind velocities of passed anemometers are to be considered. To generate "continuous" data for the ski jump simulation, linear interpolation is used between the discrete values. If the real ski jump goes beyond the L-point or is shorter than the simulated ski jump at calm wind, the last aerodynamic coefficient pair of the available set is kept constant onwards.

2.3. Analyses of the wind compensation systems

2.3.1. World cup data

In the first step, jump length and total tangential wind speed data of five exemplary world cup competition rounds of the season 2019/ 2020 were used to analyse the FIS WCS. The selection was based on the criterion of different wind conditions and includes the first or second competition rounds on the following large hills: Bischofshofen HS 142 m, Engelberg HS 140 m, Ruka HS 142 m, Sapporo HS 137 m, and Wisla HS 134 m. The data were obtained from the official result documents published by the FIS. The Pearson correlation coefficient r was determined to quantify the strength and direction of the linear relationship between the total tangential wind speed $v_{w_{tan}}$ and the jump length l. Other jump length determinants may also influence r and to minimise the influence of a major jump length determinant, the in-run velocity parallel to the ramp, only jumps from the same starting gate were included.

The jump length given in the official FIS result documents is the uncompensated jump length l_{NC} and the Pearson correlation coefficient r_{NC} quantifies the linear correlation between $v_{w_{tan}}$ and l_{NC}. The compensated jump length was computed as the difference of the uncompensated jump length and the jump length effect estimated by the FIS WCS: $l_C = l_{NC} - \Delta l_{FISWCS}$ (hill-specific parameters are given in Appendix 1). The Pearson correlation coefficient r_C quantifies the linear correlation between $v_{w_{tan}}$ and l_C and $|r_C|$ was used as a measure for the estimation accuracy. After application of the wind compensation system, $|r_C|$ is supposed to decrease and therefore, the estimation accuracy is expected to improve with decreasing $|r_C|$.

2.3.2. Computer simulation data

In the second step, computer simulation data of ski jumps in three realistic wind scenarios were used to analyse and to compare the FIS WCS and the mechanistic model-based WCS. Measurement errors were neglected.

Ski jumps of an elite athlete on the HS 140 m large hill in Garmisch-Partenkirchen were simulated using the *reference jump L2017* (Jung et al., 2018). Details of the computer simulations are described in Appendix 2. For all simulated ski jumps, the uncompensated jump length effect was computed as difference between the jump length at given wind condition and the jump length at calm wind: $\Delta l_{NC} = l_{wind} - 130$ m. The compensated jump length effect was computed as the difference of the uncompensated jump length effect and the estimated jump length effect of the given WCS: $\Delta l_C = \Delta l_{NC} - \Delta l_{WCS}$ with $\Delta l_{WCS} = \Delta l_{FISWCS}$ (hill-specific parameter for the FIS WCS is given in Appendix 1) or Δl_{MBWCS}. The compensated jump length effect can be interpreted as estimation error and $|\Delta l_C|$ was used as measure for the estimation accuracy. The estimation accuracy improves with decreasing $|\Delta l_C|$; the optimum is $|\Delta l_C| = 0$.

3. Results

3.1. Analysis of the FIS wind compensation system: World cup data

In the analysed competition rounds, the correlation between the total tangential wind speed $v_{w_{tan}}$ and the jump length varied strongly and strong variation was also seen in the estimation accuracy of the FIS WCS (Fig. 2). Strongest correlation between $v_{w_{tan}}$ and the uncompensated jump length was found in the second competition round on the HS 137 m

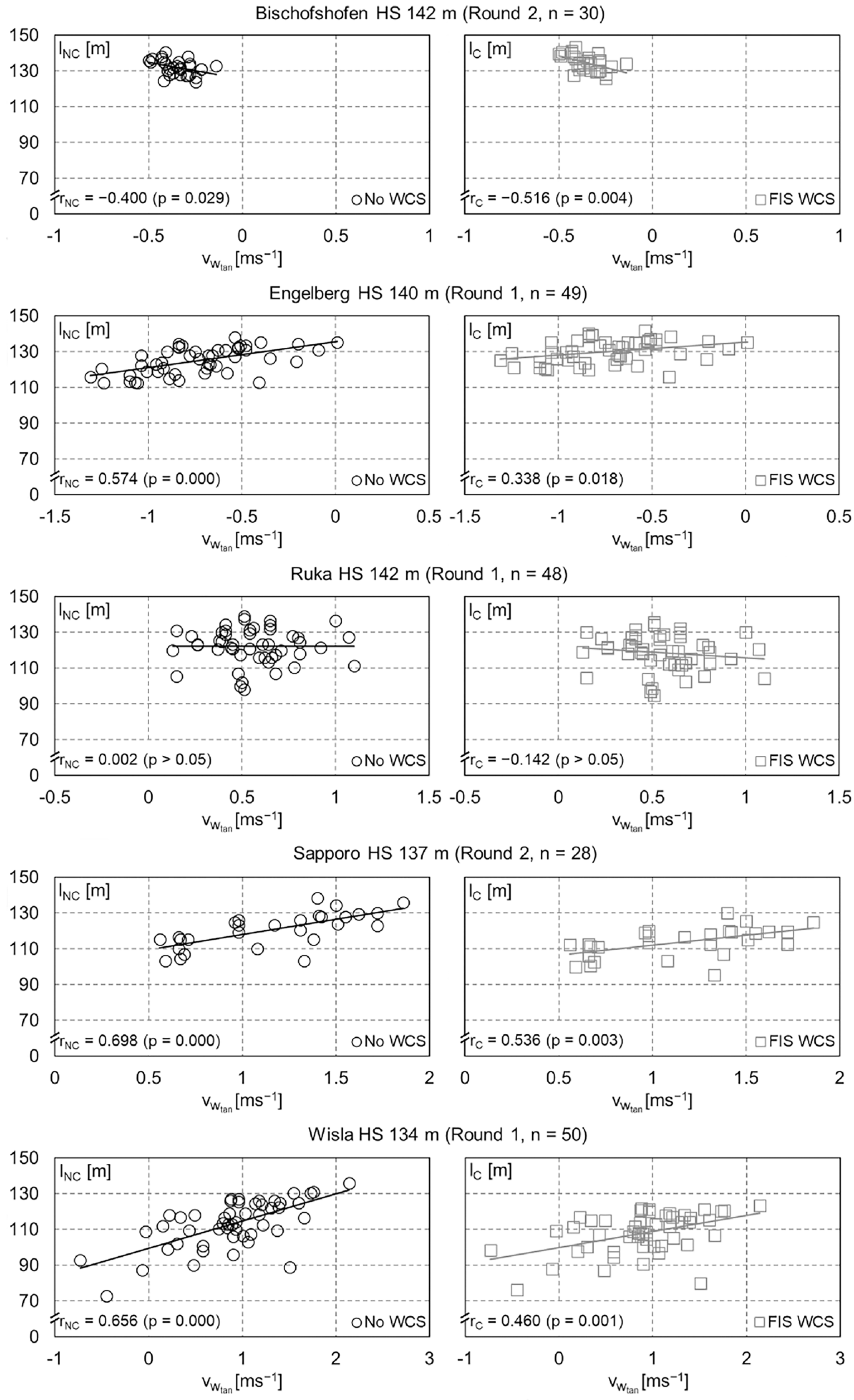

Fig. 2. Jump length l and total tangential wind speed $v_{w_{tan}}$ in five exemplary world cup runs. Data were taken from the official result documents of the FIS; the number of analysed ski jumps is denoted by n. The uncompensated jump length is termed l_{NC} and the corresponding Pearson correlation coefficient is termed r_{NC}. The compensated jump length l_C was computed by applying the FIS WCS; the corresponding Pearson correlation coefficient is termed r_C.

hill in Sapporo ($r_{NC} = 0.698$, $p = 0.000$; $n = 28$). The correlation decreased ($r_C = 0.536, p = 0.003$) after compensation. This held true for the first competition rounds on the HS 140 m hill in Engelberg, and on the HS 134 m hill in Wisla. No correlation between $v_{w_{tan}}$ and the uncompensated jump length was found in the first competition round on the HS 142 m hill in Ruka ($r_{NC} = 0.002$, $p > 0.05$, $n = 48$), which can be due to the large influence of other jump length determinants and/or due to inaccuracies associated with the determination of $v_{w_{tan}}$. The correlation was not statistical significant and the same was true for the correlation after wind compensation ($r_C = -0.142$, $p > 0.05$). Negative correlation between $v_{w_{tan}}$ and the uncompensated jump length was found in the second competition round on the HS 142 m hill in Bischofshofen ($r_{NC} = -0.400$, $p = 0.029$, $n = 30$), most likely due to inaccuracies associated with the determination of $v_{w_{tan}}$. The correlation became more negative after compensation ($r_C = -0.516$, $p = 0.004$), which indicates not only inaccurate but also misleading jump length effect estimations.

3.2. Analysis of the FIS and the mechanistic model-based wind compensation system: Computer simulation data

The results of the first wind scenario (Fig. 3) show that wind changed the jump length depending on the wind direction. The results further show that the estimation accuracy of the FIS WCS differed markedly for different wind directions. In the practically relevant wind angle ranges, the compensated jump length effect Δl_C was between 7.7 m ($\xi = 130°$) and -1.0 m ($\xi = 170°$) in headwind. This corresponds to an undercompensation by 63%, 56%, 44%, and 22% from $\xi = 130°$ to $\xi = 160°$ and an overcompensation by 31% at $\xi = 170°$. In tailwind, Δl_C was between -8.1 m ($\xi = 310°$) and 1.0 m ($\xi = 350°$). This corresponds to an undercompensation by 60%, 52%, 40%, and 21% from $\xi = 310°$ to $\xi = 340°$, and an overcompensation by 26% at $\xi = 350°$.

The results of the second wind scenario (Fig. 4) show that wind changed the jump length depending on the wind direction and on the phase of the flight in that it occurs. The results further show that the estimation accuracy of the FIS WCS differed markedly for different wind directions and flight phases in which wind occurs. Maximum $|\Delta l_C|$ was 4.9 m in headwind ($\delta = -20°$; sector 5) and 4.7 m in tailwind ($\delta = 20°$; sector 1). Headwind in the first sector decreased the jump length when δ was 0° or 20°. This was captured by the FIS WCS, although it still undercompensated the jump length effect of wind by 57% in the latter case. However, headwind with $\delta = -20°$ increased the jump length slightly and this was not captured by the FIS WCS since the processed tangential wind speed at the first anemometer is negative for any headwind direction (Appendix 1). Consequently, Δl_C is larger than Δl_{NC} and in such cases the athlete would profit not only from the wind condition itself but also from the (erroneous) wind compensation. Tailwind in the first sector increased the jump length when δ was 0° or 20°, and decreased the jump length slightly when δ was $-20°$. The latter case was captured by the FIS WCS. However, the former two cases were not captured, which is because the processed tangential wind speed at the first anemometer is negative in tangential tailwind stronger than 2 ms^{-1} (Appendix 1). Consequently, Δl_C is larger than Δl_{NC} and the athlete would again profit from the wind condition and the (erroneous) wind compensation; however, this profit is smaller compared to the headwind case described above.

The results of the third wind scenario (Table 1) show that the jump length can be left unchanged by wind that blows right after the ramp edge along the landing slope. This held true even in the extreme case of strong headwind ($v_w = 3$ ms^{-1}) blowing in a 70 m wide range from the ramp edge onwards. The results further show that the estimation accuracy of the FIS WCS depended primarily on the distance of the wind range. If the wind range included the first anemometer, maximum $|\Delta l_C|$ was 2.2 m in headwind ($v_w = 3$ ms^{-1}; $\delta = -20°$) and 3.1 m in tailwind conditions ($v_w = -3$ ms^{-1}; $\delta = -20°$). If the wind range included three or more anemometers, maximum $|\Delta l_C|$ increased to 7.2 m in headwind ($v_w = 3$ ms^{-1}; $\delta = 20°$) and tailwind ($v_w = -3$ ms^{-1}; $\delta = 20°$).

Since measurement errors were neglected in the computer simulation data, the estimation accuracy of the mechanistic model-based WCS depended only on the spatial resolution of the computed aerodynamic coefficients k_D and k_L. In a simulated ski jump at calm wind, $|\Delta l_C|$ was 0.2 m and when wind of the three wind scenarios was considered, maximum $|\Delta l_C|$ was 0.3 m (Figs. 3, 4; Table 1). This indicates that for the given spatial resolution of the computed aerodynamic coefficients (10 m) the jump length effect estimations are very accurate.

4. Discussion

The FIS WCS is a statistical-based approach for compensating the jump length effect of wind. Time-averaged tangential wind speed data are used as inputs for a linear statistical model that estimates the jump length effect. The advantages of the FIS WCS are its simplicity and the small amount of required input data associated with high "robustness". However, there is a major disadvantage: it does not include all important factors that determine the jump length effect of wind. For this reason it is not surprising that the presented analyses based on world cup competition data and computer simulation data indicate inaccurate jump length effect estimations for various wind conditions (Figs. 2–4; Table 1). This is in line with previous analyses of data of elite competitions (Aldrin, 2015; Pietschnig et al., 2020) and demonstrates that wind can still have a large impact on the competition ranking when the FIS WCS is used.

To capture the complex multifactorial jump length effect of wind in an approach that is based on a linear statistical model-based approach is impossible. Instead, mechanistic modelling could be used. The mechanistic model-based WCS introduced in the present article estimates the jump length effect as the difference between the measured jump length of the real ski jump at given wind conditions and the computed jump length of the simulated ski jump at calm wind. Inputs for the computer

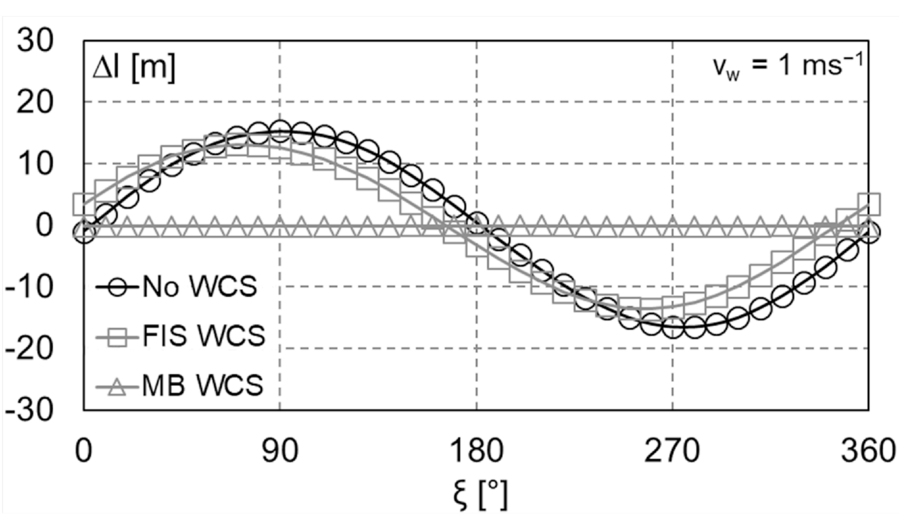

Fig. 3. Jump length effect Δl of wind in the first wind scenario. Light wind ($v_w = 1$ ms^{-1}) blew constantly throughout the entire flight and the wind angle (Fig. 1b) was varied from $\xi = 0°$ to $\xi = 360°$ in 10° increments. The practically relevant wind angle ranges are $\xi = 130–170°$ for headwind and $\xi = 310–350°$ for tailwind. Computer simulations were performed for the HS 140 m large hill in Garmisch-Partenkirchen. The uncompensated jump length effect (No WCS) and the compensated jump length effects using the FIS WCS and the mechanistic model-based WCS (MB WCS) are shown.

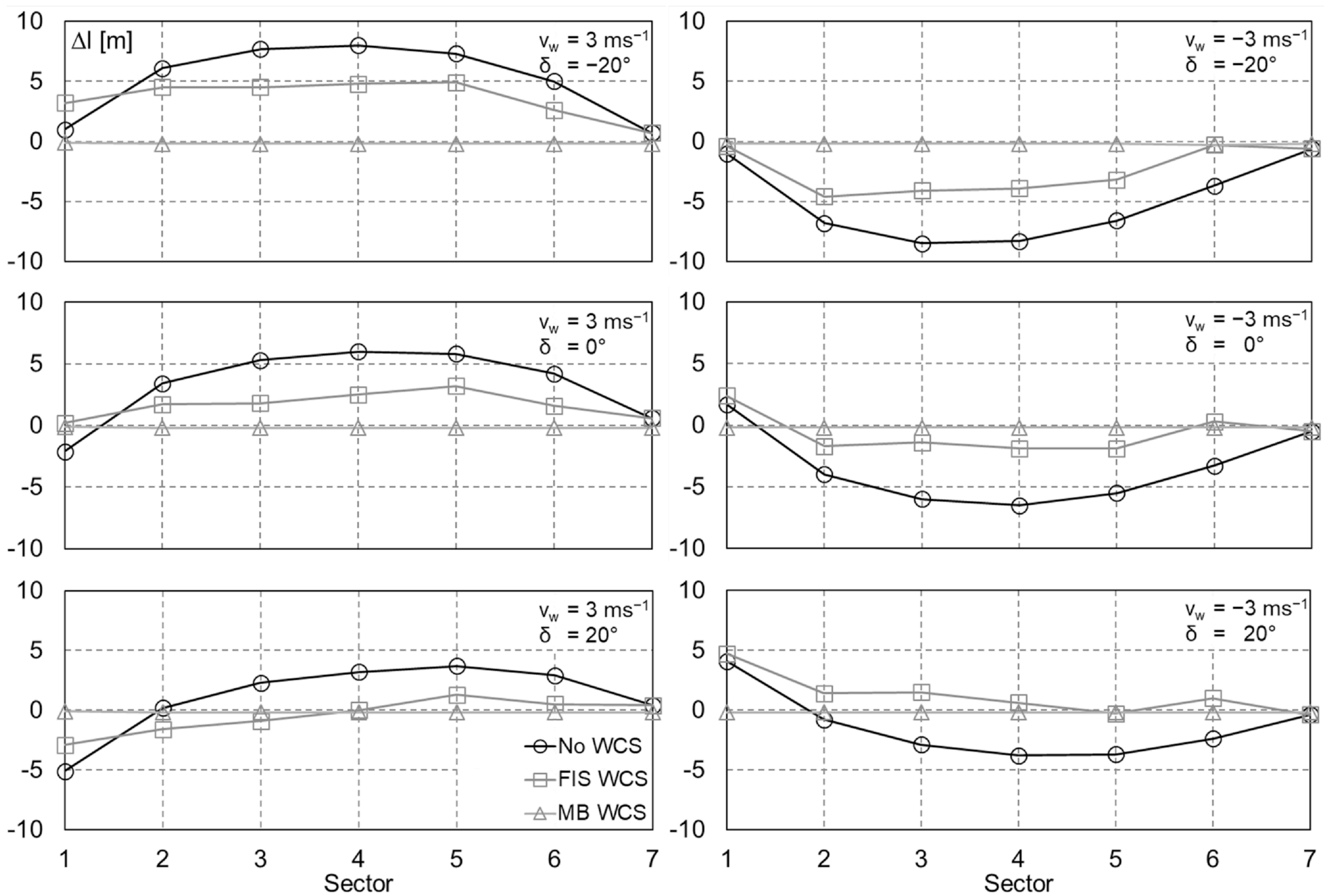

Fig. 4. Jump length effect Δl of wind in the second wind scenario. Strong wind ($v_w = \pm 3\ \mathrm{ms}^{-1}$) blew during different phases of the flight. For this, the landing slope from the ramp edge to the L-point was divided into seven sectors of 20 m each. Each sector includes one anemometer of the FIS WCS. Wind blew always only in one of these sectors, and three wind angles (Fig. 1b) were compared: tangentially to the landing slope ($\delta = 0^\circ$), flatter than the landing slope ($\delta = +20^\circ$), and steeper than it ($\delta = -20^\circ$). The uncompensated jump length effect (No WCS) and the compensated jump length effects using the FIS WCS and the mechanistic model-based WCS (MB WCS) are shown.

simulation are the initial flight velocity and aerodynamic coefficients of the real ski jump that can be obtained from kinematic and wind velocity data collected during the flight. The initial flight velocity is readily available from the kinematic data and inverse dynamics can be used to compute the aerodynamic coefficients. The advantage of the mechanistic model-based approach is that the estimation accuracy depends only on the measurement errors in the kinematic and wind velocity data because the additional errors due to the limited spatial resolution of the computed aerodynamic coefficients can be kept below the error margin of relevance in ski jumping. When applied to simulated ski jumps in three realistic wind scenarios and by neglecting measurement errors, the maximum estimation error was smaller than the jump length measurement resolution in a competition that is 0.5 m. Consequently, it can be concluded that the estimation accuracy depends only on the measurement error of the collected kinematic and wind velocity data.

Kinematic and wind velocity data could be collected by measurement systems that are already used by the FIS in practice: anemometers that are installed along the landing slope, and inertial measurement units (IMUs) that are fixed at both skis behind the binding, combined with the ultra-wide band (UWB) technology with multiple antennas around the hill (Swiss Timing, Switzerland). Examples for the use of IMUs to collect kinematic data in ski jumping can also be found in the literature (Chardonnens et al., 2014; Groh et al., 2017; Fang et al., 2020). In addition to the flight acceleration and the flight velocity data, the IMUs combined with the UWB technology can collect the corresponding flight path coordinates. Knowing the positions of the ramp edge and the anemometers, this has the advantages that the initial flight velocity could be obtained from the collected flight velocity data and that the collected kinematic and wind velocity data could be matched. Once all required data are available after landing, the computation of the aerodynamic coefficients and the simulation of the ski jump in calm wind can be performed on a regular personal computer within a few seconds only. In future work, measurement errors of available measurement systems should thoroughly be determined to figure out the resulting estimation deviations of the mechanistic model-based approach.

Wind-induced changes of the airflow velocity do not only affect the aerodynamic forces but also the pitching moment. The athlete may respond with flight technique modifications to increase the jump length (Jung et al., 2019) or only to prevent tumbling, in particular when strong crosswind gusts occur. Flight technique modifications additionally change the aerodynamic forces and thus the jump length and can be understood as secondary jump length effect of wind. This secondary jump length effect of wind cannot be considered in any mathematical compensation approach because it is unknown how the flight technique would have looked like in calm wind.

Crosswind components of wind are not taken into account in the presented mathematical compensation approaches. It is assumed that crosswind components affect the jump length rather by the secondary than by the primary jump length effect and therefore, the installation of sufficiently large wind nets along the landing slope is considered the method of choice for improving fairness in competitions.

Ski jumping will likely remain an open air sport: the ultimate question to be discussed by athletes, coaches, and FIS representatives is

Table 1
Jump length effect Δl of wind in the third wind scenario. Wind blew between the ramp edge and the turn-over point. This is the point at which the sign of the jump length effect of wind changes (i.e. $\Delta l = 0$) and the distance l_{to} from the ramp edge is measured along the landing slope. The number of anemometers n_A within the wind range is given. Headwind blew with $v_w = (1, 2, 3)\ \mathrm{ms}^{-1}$, and tailwind blew with $v_w = (-1, -2, -3)\ \mathrm{ms}^{-1}$ tangentially to the landing slope ($\delta = 0^\circ$), or with a deviation of $\delta = \pm 20^\circ$ from it. The uncompensated jump length effect (No WCS) is per definition of the turn-over point always 0 and the compensated jump length effects using the FIS WCS and the mechanistic model-based WCS (MB WCS) are also given.

v_w [ms^{-1}]	δ [°]	l_{to} [m] (n_A)	Δl [m]		
			No WCS	FIS WCS	MB WCS
1	−20	15.3 (1)	0.0	0.7	−0.1
	0	33.3 (1)	0.0	0.0	−0.1
	20	72.3 (3)	0.0	−2.4	−0.1
2	−20	14.8 (1)	0.0	1.5	−0.1
	0	33.4 (1)	0.0	0.0	−0.1
	20	74.9 (3)	0.0	−4.8	−0.1
3	−20	14.5 (1)	0.0	2.2	−0.1
	0	33.7 (1)	0.0	0.0	−0.1
	20	77.9 (4)	0.0	−7.2	−0.1
−1	−20	13.9 (1)	0.0	−0.6	−0.2
	0	31.4 (1)	0.0	0.0	−0.2
	20	66.0 (3)	0.0	2.9	−0.2
−2	−20	14.4 (1)	0.0	−0.1	−0.2
	0	31.3 (1)	0.0	1.5	−0.2
	20	64.3 (3)	0.0	4.3	−0.2
−3	−20	14.7 (1)	0.0	0.6	−0.2
	0	31.2 (1)	0.0	3.1	−0.2
	20	62.4 (3)	0.0	7.2	−0.3

whether jump length effects of wind should be compensated by mathematical approaches at all. Over the entire world cup season, wind effects will largely cancel out as every single athlete will experience many advantageous and many disadvantageous wind conditions (Müller, 2009). In accordance, a solution strategy for single competitions like World Championships or Olympic Games could be to conduct a larger number of rounds. This is already practised in the Ski Flying World Championships, where four rounds are conducted. However, wind is a chaotic phenomenon and changes arbitrarily; consequently, fairness is never guaranteed.

Mathematical wind compensation offers the opportunity to react to wind in every single ski jump and it was demonstrated that the presented mechanistic model-based approach can estimate the jump length effect of wind with higher accuracy as obtainable with an approach based on a linear statistical model. Therefore, we suggest to test it in parallel to the FIS WCS in real-world competitions.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2021.110585.

References

Aldrin, M., 2015. Fair compensation for gate and wind conditions in ski jumping – estimated from competition data using a mixed model. J. Quant. Anal. Sports 11 (4), 231–245.

Chardonnens, J., Favre, J., Cuendet, F., Gremion, G., Aminian, K., 2014. Measurement of the dynamics in ski jumping using a wearable inertial sensor-based system. J. Sports Sci. 32 (6), 591–600.

Denoth, J., Luethi, S.M., Gasser, H.H., 1987. Methodological problems in optimization of the flight phase in ski jumping. Int. J. Sport Biomech. 3 (4), 404–418.

Fang, X., Grüter, B., Piprek, P., Bessone, V., Petrat, J., Holzapfel, F., 2020. Ski jumping trajectory reconstruction using wearable sensors via extended Rauch-Tung-Striebel smoother with state constraints. Sensors 20 (7), 1995.

International Ski Federation, 2009. FIS Fact Sheet. Important new rules in ski jumping and Nordic combined Summer Grand Prix. International Ski Federation (FIS), Oberhofen, Switzerland.

International Ski Federation (FIS), 2016. FIS Fact Sheet. Wind and in-run compensation. FIS, Oberhofen, Switzerland.

Groh, B.H., Warschun, F., Deininger, M., Kautz, T., Martindale, C., Eskofier, B.M., 2017. Automated ski velocity and jump length determination in ski jumping based on unobtrusive and wearable sensors. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 1 (3), 53.

Jung, A., Staat, M., Müller, W., 2014. Flight style optimization in ski jumping on normal, large, and ski flying hills. J. Biomech. 47 (3), 716–722.

Jung, A., Müller, W., Staat, M., 2018. Wind and fairness in ski jumping: a computer modelling analysis. J. Biomech. 75, 147–153.

Jung, A., Müller, W., Staat, M., 2019. Optimization of the flight technique in ski jumping: the influence of wind. J. Biomech. 88, 190–193.

König, H., 1952. Theorie des Skispringens angewandt auf die Flugschanze in Oberstdorf, Uhrentechnische Forschung - Vom Skisprung zum Skiflug. J.F. Steinkopf Verlag, Stuttgart, pp. 235-253.

Müller, W., Platzer, D., Schmölzer, B., 1995. Scientific approach to ski safety. Nature 375, 455.

Müller, W., Platzer, D., Schmölzer, B., 1996. Dynamics of human flight on skis: improvements on safety and fairness in ski jumping. J. Biomech. 29 (8), 1061–1068.

Müller, W., 2009. Determinants of ski-jump performance and implications for health, safety and fairness. Sports Med. 39 (2), 85–106.

Pietschnig, J., Pellegrini, M., Eder, J.S.N., Siegel, M., 2020. After all, it is an outdoor sport: meta-analytic evidence for negative associations between wind compensation points and round scores in ski jumping competitions. PLoS One 15 (8), e0238101.

Schmölzer, B., Müller, W., 2002. The importance of being light: aerodynamic forces and weight in ski jumping. J. Biomech. 35 (8), 1059–1069.

Straumann, R., 1927. Vom Skiweitsprung und seiner Mechanik. In: Jahrbuch des Schweizerischen Ski Verbandes, Schweizerischer Ski Verband, Bern, pp. 34-64.

Virmavirta, M., Kivekäs, J., 2012. The effect of wind on jumping distance in ski jumping – fairness assessed. Sports Biomech. 11 (3), 358–369.

Virmavirta, M., Kivekäs, J., 2019. The effect of wind on jumping distance in ski jumping depends on the aerodynamic polar. In: 27th Congress of the International Society of Biomechanics, 31st July – 4th August, Calgary, Canada, p. 612.