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Wind and fairness in ski jumping: A computer modelling analysis

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ABSTRACT

Wind is closely associated with the discussion of fairness in ski jumping. To counter-act its influence on the jump length, the International Ski Federation (FIS) has introduced a wind compensation approach. We applied three differently accurate computer models of the flight phase with wind (M1, M2, and M3) to study the jump length effects of various wind scenarios. The previously used model M1 is accurate for wind blowing in direction of the flight path, but inaccuracies are to be expected for wind directions deviating from the tangent to the flight path. M2 considers the change of airflow direction, but it does not consider the associated change in the angle of attack of the skis which additionally modifies drag and lift area time functions. M3 predicts the length effect for all wind directions within the plane of the flight trajectory without any mathematical simplification. Prediction errors of M3 are determined only by the quality of the input data: wind velocity, drag and lift area functions, take-off velocity, and weight. For comparing the three models, drag and lift area functions of an optimized reference jump were used. Results obtained with M2, which is much easier to handle than M3, did not deviate noticeably when compared to predictions of the reference model M3. Therefore, we suggest to use M2 in future applications. A comparison of M2 predictions with the FIS wind compensation system showed substantial discrepancies, for instance: in the first flight phase, tailwind can increase jump length, and headwind can decrease it; this is opposite of what had been anticipated before and is not considered in the current wind compensation system in ski jumping.

1. Introduction

Ski jumping competitions are held on three types of hills differing in hill size, HS (distance between the edge of the ramp and the L-point on the landing slope surface, Fig. 1a): normal hills (85–109 m), large hills (110–184 m), flying hills (≥185 m) (Gasser, 2012). Performance factors are the in-run velocity parallel to the ramp $\mathbf{v}_0$, the take-off velocity perpendicular to the ramp $\mathbf{v}_{p0}$, the gravitational force $\mathbf{F}_g$, and the time courses of the aerodynamic drag $\mathbf{F}_d$ and lift force $\mathbf{F}_l$ during the flight (Straumann, 1927; König, 1952; Denoth et al., 1987, Müller et al., 1995, 1996). Aerodynamic forces depend on the drag area D and lift area L and are additionally influenced by the wind speed and direction. Drag and lift areas are functions of the flight position which is controlled by the athlete. Straumann (1927) developed the equations of motion in the plane of the flight trajectory for the first time. Remizov (1984) was the first to apply optimal control theory (Pontryagin's minimum principle, Pontryagin et al., 1962) for optimizing the time function of the angle of attack of the body of a ski jumper with skis held parallel. Boklöv introduced the V-style in 1985, which is associated with higher aerodynamic forces (Müller et al., 1996); since, the flight technique (time course of the flight position angles) has become the predominant performance factor.

Computational fluid dynamics (CFD) is yet not capable to compute the lift and drag areas of a ski jumper in his equipment with sufficient accuracy (Meile et al., 2006). Müller et al. (1995, 1996) were the first to use time functions of drag and lift areas based on field studies of flight positions during competitions and on wind tunnel measurements for highly realistic computer simulations of V-style ski jumping. This approach was further developed and applied to study various scientifically and practically relevant topics in ski jumping (Schmölzer and Müller, 2002; 2005; Müller et al., 2006; Müller, 2009a; 2009b). Jung et al. (2014) applied Pontryagin's minimum principle to optimize the time courses of both the angle of attack α of the skis and the body-to-ski angle β (Fig. 1a). They found that substantially different time courses can result in similar jump lengths, even for one given athlete with his individual set of drag and lift areas (as functions of the flight positions). This is in line with field study results during the

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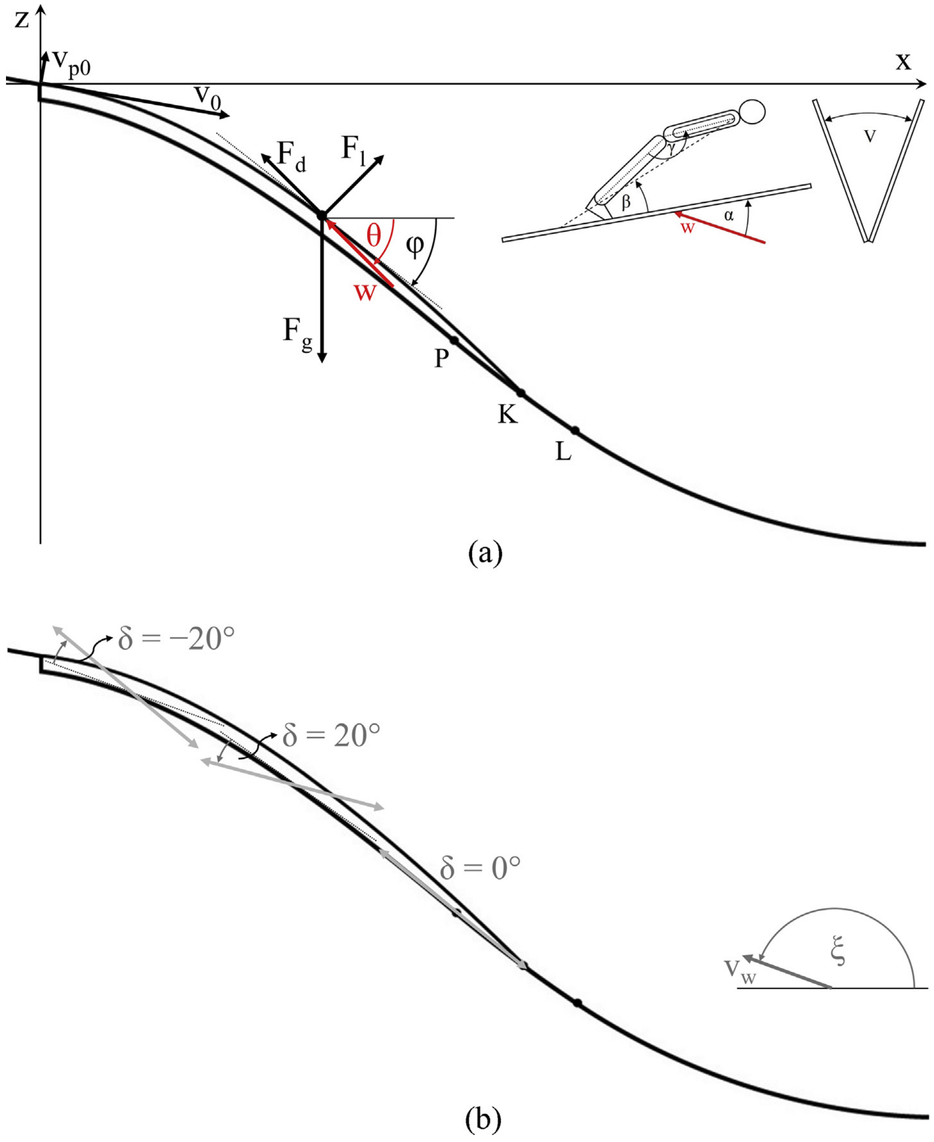

Fig. 1. Model of the flight phase of ski jumping: terminology. (a) The flight path of a ski jumper depends on two initial conditions (in-run velocity parallel to the ramp $\mathbf{v}_0$ and take-off velocity perpendicular to the ramp $\mathbf{v}_{p0}$) and three forces (gravitational force $\mathbf{F}_g$, drag force $\mathbf{F}_d$, and lift force $\mathbf{F}_l$). Flight position angles are: angle of attack of the skis α relative to the airflow $\mathbf{w}$, body-to-ski angle β, hip angle γ, and V -angle of the skis to each other. The flight path angle is denoted with φ; θ is the airflow angle; they are measured with respect to the horizontal line (and have negative values during the flight). The hill profile was modelled according to the hill parameters (FIS Certificate of Jumping Hills). For the computer simulations, the profile of the large hill (HS 140 m) in Garmisch-Partenkirchen (201/GER 24) was used. (b) Schematic drawing: wind $\mathbf{v}_w$ in the x - z -plane was considered in the computer model; ξ is the wind angle relative to the horizontal, which was counted positive in counter-clockwise direction. The figure shows schematically wind blowing (within the plane of the flight path) tangentially to the landing slope ($\delta = 0°$), or with a deviation of $\delta =$ +20° or −20° from it.

Olympic Games 2002 which illustrated that the medalists used distinctively different flight techniques (Schmölzer and Müller, 2005). Jung et al. (2015) considered wind for the first time as a possible factor influencing flight technique optimizations.

Wind changes the speed and direction of the airflow and thus also the angle of attack of the skis. The resulting change in jump length depends on wind speed and direction, the flight technique, the hill size, and the flight phase in which wind occurs. Previous computer simulations, which have used a simplified wind model, have suggested that headwind increases jump length whereas tailwind decreases it, and that tailwind has a larger effect on the jump length than headwind (Müller et al., 1996; Schmölzer and Müller, 2002; Virmvirta and Kivekäs, 2012).

To counter-act the wind influence on jump length, the International Ski Federation (FIS) has introduced a wind compensation system (WCS) in 2009 (FIS, 2016; Appendix). Aldrin (2015) found when analyzing 80 international competitions that the average length effect according to the WCS was too low by 48% for headwind, and by 22% for tailwind.

Müller et al. (1996), and Schmölzer and Müller (2002) used equations of motion where the magnitude of the airflow velocity $\mathbf{w} = \mathbf{v}_w - \mathbf{v}$ was used for computing the aerodynamic forces (M1). The wind effect predictions of this model are accurate in conditions when wind blows in direction of the flight velocity $\mathbf{v}$, or opposite to it, but for wind blowing with velocity $\mathbf{v}_w$ in a direction that deviates from the tangent to the flight path, inaccuracies are to be expected. Virmvirta and Kivekäs, (2012) used the same equations, but drag- and lift area functions used are not specified there.

Here, two novel models, M2 and M3, are introduced. M3 calculates the aerodynamic force components relative to the actual airflow and also includes corrections of the drag and lift area time functions due to changes of the angle of attack when $\mathbf{w}$ deviates from the direction of $\mathbf{v}$. Model M3 predicts the jump length effect of wind for all wind directions in the plane of the flight trajectory

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