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OPTIMIZATION OF THE FLIGHT STYLE IN SKI JUMPING

Alexander Jung[1]*, Manfred Staat[1] and Wolfram Müller[2]

[1] Aachen University of Applied Sciences, Jülich Campus, Institute of Bioengineering, Biomechanics Lab., Heinrich-Mußmann-Str. 1, 52428 Jülich, Germany, alexander.jung1@alumni.fh-aachen.de, staat@fh-aachen.de, http://www.fh-aachen.de/forschung/institut-fuer-bioengineering/

[2] Medical University of Graz, Institute of Biophysics, Harrachgasse 21/4, 8010 Graz, Austria, wolfram.mueller@medunigraz.at, http://www.meduni-graz.at/biophysik/

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At a given ski jumping hill the jump length depends on the initial conditions, i.e. the inrun velocity (v_0), the take-off velocity perpendicular to the ramp (v_{p0}), and the forces that act on the athlete and his equipment, i.e. the gravitational force (F_g) and the aerodynamic forces drag (F_d) and lift (F_l). Straumann was the first to publish the equations of motion (1927[1]) which provide the basis for analyzing ski jumping. The athlete can influence the aerodynamic forces by changing his flight position characterized by the angle of attack α, the body-ski angle β, the hip angle γ, and the V-angle (angle of the skis to each other). In parallel, he has to control the pitching moment, which also depends on his flight position, to keep the flight stable. Drag (D) and lift areas (L) can be determined in wind tunnel measurements and are used as a time depending input to consider flight positions changes in the equations of motion[2]. Since the V-Style was introduced by Jan Boklöv in 1985, the aerodynamic strategy of the athlete has become predominantly important in ski jumping[2]. Remizov was the first to examine the optimal flight style with respect to the angle of attack (1984[3]) by using Pontryagin´s minimum principle[4]. He has shown that α should increase in a convex way during the flight phase to obtain maximum jump length. As mentioned above, the flight style is constrained by the flight stability. In our optimization studies we took the angle of attack as well as the body-ski angle into account and combined Pontryagin´s minimum principle with a penalty function derived from flight position constraints[5]. A comprehensive set of accurate wind tunnel data[6][7] was used for this purpose, but due to missing detailed aerodynamic data for the initial flight phase this optimization starts at $t = 0.7$ s. Up to that time point, data of the reference jump A[7] were used. By varying the constraints it was recently shown that there are various possibilities to reach comparable jump lengths and individual athletes have to develop their individual optimum which is to be tuned with their personal features and abilities[5]. That corresponds to a field study during the 2002 Winter Olympic Games which illustrated that the medallists used distinctively different flight styles[8]. The impact of aerodynamic forces on jump length strongly increases on ski flying hills compared to large and normal hills[2][5]. For this reason, athletes have to adjust their flight style in ski flying competitions[5]. Fig. 1 shows the optimized flight styles on the ski flying hill according to the range of $v_{p0} =$ 2-3 ms^{-1} observed in elite ski jumping[2]. Although jump lengths differ substantially (166.4 m, 178.4 m and 188.3 m, respectively), the flight style differences for obtaining the maximum jump length at each v_{p0} are small: application of the flight style optimized for $v_{p0} = 2.5$ ms^{-1} to the jumps with $v_{p0} = 2.0\ \mathrm{ms}^{-1}$ and $v_{p0} = 3.0\ \mathrm{ms}^{-1}$ results in a maximum jump length decrease of only 1.3 m at the ski flying hill. Therefore, $v_{p0} = 2.5\ \mathrm{ms}^{-1}$ can be used as a representative value for optimization studies in elite ski jumping.

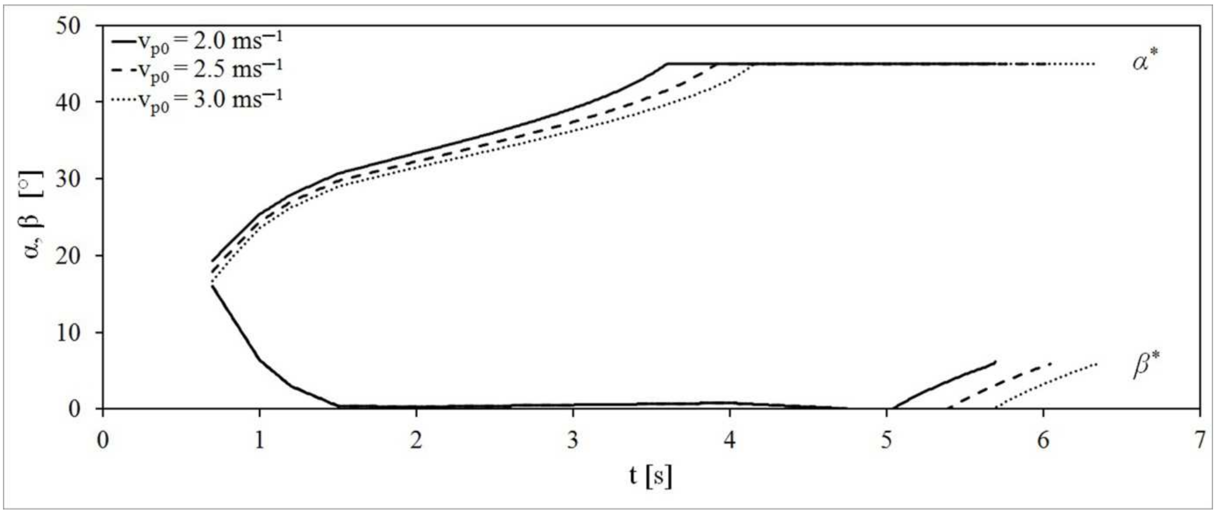

Fig. 1. Optimized time courses $\alpha^*(t)$ and $\beta^*(t)$ on the ski flying hill (Harrachov, CZ, HS 205 m). An inrun velocity of $v_0 = 28.5\ \mathrm{ms}^{-1}$ was used according to the FIS certificate of jumping hill. Flight position constraints were $\alpha_{max} = 45°$ and $\beta_{min}(t) = \beta_{ref\ A}(t) - 10°$ with $\beta_{min}(t) \geq 0°$ and $\beta_{ref\ A}(t)$ being the β-time course of reference jump A[7]. These constraints were chosen with respect to a barely stable flight[5].

Optimization studies can be used advantageously for guiding the training in elite ski jumping. Future studies should be based on detailed wind tunnel data including the initial flight phase. This would provide improved arguments for constraining flight positions in optimization studies and give a more detailed understanding of individual flight style optimization.

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