Journal of Biomechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Numerical investigation of the early flight phase in ski-jumping

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ARTICLE INFO

Article history:
Accepted 13 May 2017
Available online xxxx

Keywords:
Computational Fluid Dynamics (CFD)
Ski-jump
Lift-to-drag ratio
Aerodynamic

ABSTRACT

The purpose of this study is to develop a numerical methodology based on real data from wind tunnel experiments to investigate the effect of the ski jumper's posture and speed on aerodynamic forces in a wide range of angles of attack. To improve our knowledge of the aerodynamic behavior of the ski jumper and his equipment during the early flight phase of the ski jump, we applied CFD methodology to evaluate the influence of angle of attack (α = 14°, 21.5°, 29°, 36.5° and 44°) and speed (u = 23, 26 and 29 m/s) on aerodynamic forces in the situation of stable attitude of the ski jumper's body and skis. The standard $k-\omega$ turbulence model was used to investigate both the influence of the ski jumper's posture and speed on aerodynamic performance during the early flight phase. Numerical results show that the ski jumper's speed has very little impact on the lift and drag coefficients. Conversely, the lift and drag forces acting on the ski jumper's body during the early flight phase of the jump are strongly influenced by the variations of the angle of attack. The present results suggest that the greater the ski jumper's angle of inclination, with respect to the relative flow, the greater the pressure difference between the lower and upper parts of the skier. Further studies will focus on the dependency of the parameters with both the angle of attack α and the body-ski angle β as control variables. It will be possible to test and optimize different ski jumping styles in different ski jumping hills and investigate different environmental conditions such as temperature, altitude or crosswinds.

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1. Introduction

Ski jumpers seek to maximise the length of their ski-jump. The flight distance, stability and the ski jumper's posture are the primary criteria that determine a ski jump score (Yamamoto et al., 2016; Schwameder, 2008). Therefore, the aerodynamics of the ski jumper (and his equipment) is an essential performance factor. The flight performance is influenced by factors such as the release speed, the body angle of the ski jumper, the aerodynamic and gravitational forces, and the landing stability of the ski jumper (Schmölzer and Müller, 2002, 2005; Virmavirta, 2016). Among these criteria, the body angle of the ski jumper which affects the aerodynamics forces, have a primary effect on the length of the jump. Additionally, the ski jumper's angle of attack (incidence relative to the velocity vector) and the flight path angle (velocity vector inclination to the horizontal) are fundamental factors that determine the distance achieved during a ski-jump (Remizov, 1984). During the flight phase, drag force, acting negatively in the horizontal plane of flying, must be minimized (Vodicar and Jošt, 2011).

During the ski jumper's flight, the gravitational force F_g, the lift force F_l, and the drag force F_d acting upon the ski jumper can be expressed by (Müller, 2005):

$$F_g = mg;\ F_l = \frac{\rho}{2}v^2c_lA = \frac{\rho}{2}v^2L;\ F_d = \frac{\rho}{2}v^2c_dA = \frac{\rho}{2}v^2D, \qquad (1)$$

where m (kg) is the mass of the system; g (m/s^2) is the gravitational acceleration; ρ (kg/m^3) is the density of air, A (m^2) is the projected frontal area of the skier (perpendicular to the velocity vector); c_d and c_l are the drag and lift coefficients, respectively, which depends on α (°), the angle of attack, $L = c_lA$ and $D = c_dA$.

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http://dx.doi.org/10.1016/j.jbiomech.2017.05.013
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In the run-phase, ski jumpers keep their bodies in a position that reduces air drag as much as possible, which facilitates maximal speed on the take-off ramp (Schwameder and Müller, 2001). Finally, and once in the air, ski jumpers change their posture and the position of their skis to maximise air lift, thus increasing the length of their jump (Schmölzer and Müller, 2002). It is well known that performance in ski jumping is determined not only by the athletic capacity of the ski jumper, but also by the aerodynamic features of the equipment used such as the ski suits. Recently, studies by Chowdhury et al. (2010, 2011) have revealed that textile materials used in high performance sports, in addition to the ski jumper's body position, are crucial for overall performance. By adjusting body posture, a ski jumper can alter the aerodynamic forces on his body (Müller, 2005; Virmavirta, 2016). The ski jumper's position can affect the drag force, the lift force and the torque, and thereby strongly influence changes in his flight position relative to the air stream (Müller, 2005).

Therefore, the ski jumper's posture has been variously considered by the use of mathematical methods, wind tunnel experiments, video analysis or computational fluid dynamics (CFD). Meile et al. (2006) studied how ski jumping suits influence drag and lift forces, and have determined the optimal body angle. Using wind tunnel experiments, Müller (2005) reported the optimum angle of a ski jumper's body to maximize the lift-to-drag ratio. Chowdhury et al. (2011) studied the effects of the ski suit on ski jumper's aerodynamic performance and showed that the tight fit suit provides an extra aerodynamical advantage over a normal-fit suit. Seo et al. (2004) have assessed the aerodynamic forces during the free flight phase by using a full-size model in a wind tunnel. However, wind tunnel measurements are very expensive and require the availability of several world class ski jumpers over a lengthy period.

In recent years, many researchers have used the Computational Fluid Dynamics (CFD) method to perform studies on the aerodynamics of ski jumping (Hanna, 1996; Nørstrud and Øye, 2009; Marqués-Bruna and Grimshaw, 2009; Latchman and Pooransingh, 2016). In order to achieve highly realistic computer simulations, it is necessary to simulate as accurately as possible the ski jumper and his equipment (e.g. skis, boots, gloves, underwear). However, most of these numerical studies have been conducted from simplified models. Meile et al. (2006) used combinations of simple geometries to represent human bodies, leading to poor agreement between the CFD results and the experiments. Lee et al. (2012) employed a Kriging model to study both the effect of a ski jumper's geometrical variations on the lift-to-drag ratio and the optimum posture of the ski jumper. Rudakov and Podgayets (1998) considered the problem in a 2D statement and used a simplified model to investigate the turbulent airflow around the ski jumper.

The aim of this research is to evaluate both the influence of a ski jumper's posture and speed on aerodynamic forces when the attitude of the ski jumper's body and skis remains stable during the early flight phase of the ski jump. Moreover, the methodology we apply can be parameterized and produce computer generated results that require reduced computation time relative to other existing methods, allowing researchers to efficiently evaluate the effect of skier's posture and speed or weather conditions on aerodynamic forces.

2. Method

The present study was approved by our institutional ethics committee. Written informed consent was signed by each participant before taking part in this study.

We used a numerical method that applies Computational Fluid Dynamics (CFD). This method can be used as a computationally fast and powerful investigative tool for studying the aerodynamic behavior of the ski jumper during the flight phase. In this study, we used a 3D model generated from laser scanning and VICON measurements, a method in which multiple cameras are used. This method offers a highly realistic approach and constitutes a technological advance compared to previous studies in the field (Meile et al., 2006; Lee et al., 2012; Rudakov and Podgayets, 1998). The numerical model of the ski jumper's body was obtained by scanning a world-class skier and his standard equipment (ski jumper's height: 1.79 m; ski length: 2.6 m) in ski jump position (stable flight posture). In order to obtain the geometry of the ski jumper, measurements were performed using a VICON system including 8 cameras. These measures (3D points) were combined with anthropometric data obtained using a laser scanner. The methodology is accurately described in a previous paper (Gardan et al., 2015). Once the ski jumper's geometry was re-constructed with the VICON data, the next step was to create the fluid domain around the ski jumper (Fig. 1). Virtual Wind Tunnel (VWT) was used to create the fluid domain as described in a previous paper (Gardan et al., 2015). We referred to the parametric study performed by Zaïdi et al. (2008) to define the size of the fluid domain, namely 3 m upstream and 10.8 m downstream from the skier. The computational grid was performed using the Altair Hypermesh© software with triangular and hexahedral cells and consists of about 5 million elements. To reduce computation time, the meshing was constructed in a progressive three-dimensional grid, refined near the surface of the ski jumper and coarse near the frontiers of the domain.

2.1. Boundary conditions

The boundary conditions adopted for the numerical simulations are as follows:

- At the inlet of the fluid domain, a uniform constant horizontal speed is imposed. To take account of the variation in the speed during the take-off, simulations were performed for velocities ranging from 23 to 29 m/s (23, 26, 29 m/s) corresponding to the range of inrun velocities according to various field studies (FIS official measurements) (Schmölzer and Müller, 2002).
- At the outlet of the fluid domain, ambient static pressure is imposed.
- On the upper and side surfaces of the fluid domain: a slip-wall boundary (symmetry) is imposed.
- On the surface of the ski jumper model, the no-slip wall boundary condition is imposed.

The fluid domain was specified as incompressible air, with the density of 1 kg/m^3 and a viscosity of 1.8×10^{-5} kg/(m/s) corresponding to an altitude close to 2000 m (Sochi Olympic Games, 2014).

2.2. CFD simulation

Simulations were performed using Altair Acusolve© CFD code. For each studied case, simulations were conducted using 4 processors (32 Go RAM). Initial differences in the resulting drag forces, as generated by each processor, were reduced by incremental parameter adjustments until the results converged. This steady state was obtained after approximately 2 h 30 min of calculation. Solutions were obtained using the standard k-ω model which is perfectly adapted to detect recirculation (Zaïdi et al., 2010). This turbulence model is widely used for wall-bounded flows like the flow around the body contour of the ski jumper.

The 3D model dimensions used in our current study corresponds to a typically world-class ski jumper (Gardan et al., 2015). Postures and positions analysed in the present study are characterized by the angles represented in Fig. 2 which represents the ski-jumpers in usual flight position: α is the angle of attack, β the body angle relative to the skis, and γ is the hip angle. During the flight phase, ski jumpers tend to modify their posture and flight position to improve aerodynamics. In this analysis, we studied both the influence of the angle of attack α and the speed on the aerodynamic performance of the ski jumper. For this purpose, we considered the angle of attack α which was varied from 14 to 44° relative to horizontal plane ($\alpha = 14°$, 21.5°, 29°, 36.5° and 44°) as well as the speed of the ski jumper, which was also varied from 23 to 29 m/s (u = 23, 26 and 29 m/s). The maximum value of α is set to 44° which is close to the largest angles observed in the field (Müller et al., 1996;

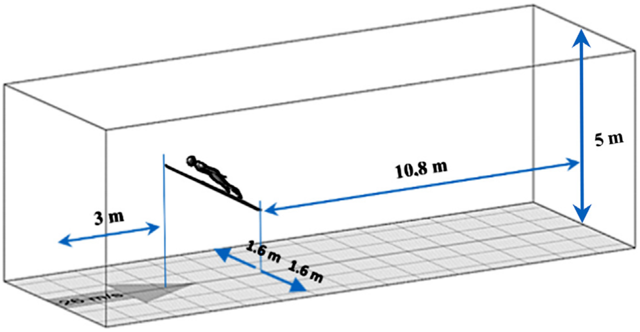

Fig. 1. Geometry of the used computational domain.

Please cite this article in press as: Gardan, N., et al. Numerical investigation of the early flight phase in ski-jumping. J. Biomech. (2017), http://dx.doi.org/10.1016/j.jbiomech.2017.05.013

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