EFFECT OF POSTURAL CHANGE ON THE AERODYNAMIC CHARACTERISTICS DURING TAKEOFF IN SKI JUMPING

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The purpose of this study was to quantify the aerodynamic characteristics during takeoff using computational fluid dynamics (CFD). The CFD method adopted for this study is based on Large–Eddy Simulation. Body surface data were obtained by 3-D laser scanning of an active ski jumper. A model was generated by dividing the data into 15 segments with joint mobility. Based on video analysis of the actual takeoff movement at a jumping hill, two sets of motion data were generated (world-class jumper A and less-experienced junior jumper B). The incoming velocity was set to 23.23 m/s. The aerodynamic force, flow velocity, and vortices for each model were compared between models. Comparison of the two models shows that aerodynamic forces acting upon models might be influenced by the airflow condition around the model's back. Expansion of the low air-speed domain of jumper B can be caused by a large trunk angle of attack (Meile et al., 2006). The trunk and upper arm motion might cause the flow structure difference of the wake. Two distinct vortexes generated by the arms produced a downwash flow in the wake of jumper A. It is considered that the positioning of the arms in a very low position strongly influences the flow structure. These results suggested that the vortexes generated by the arms seem to be very important for the aerodynamic lift generation.

KEY WORDS: ski jumping, computational fluid dynamics, aerodynamic force, vortex.

INTRODUCTION: The ski jumping takeoff motion is the transition movement from the in-run posture to the flight posture. Take-off is considered to be the most important phase for the entire ski jumping performance because it sets the initial flight conditions (Virmavirta and Komi, 1989, Arndt et al., 1995, Virmavirta et al., 2009). During takeoff, the athlete performs a body extension to raise his/her center of mass and to gain a forward-rotating angular momentum (Schwameder, 2008). The ski jumper must perform an appropriate takeoff movement for an aerodynamic force to form a suitable flight posture in a short period (Yamamoto et al., 2012). According to Virmavirta et al. (2001), the ski jumper receives lift during this movement and lets them shorten the takeoff time. However, the relationships between the motion and the aerodynamic characteristics during the motion remain obscure. Therefore, ski jumpers try to optimize their motion for aerodynamic forces by means of field tests or wind-tunnel tests (Virmavirta et al., 2011). With these disciplines, the aerodynamic improvements are usually assessed by trial and error, by evaluating the drag reduction. However, this method cannot visualize or analyze the flow field around the ski jumper. An alternative method, which analyzes both aerodynamic forces and detailed flow-field information during the motion, is computational fluid dynamics (CFD). This technique has recently been used in the flight phase of ski jumping (Lee et al., 2012; Meile et al., 2006). The CFD technique would be the effective means to analyze detailed flow field during takeoff movement. The purpose of this study was to evaluate the influence of postural change on aerodynamic characteristics during takeoff using CFD.

METHODS: In the present study, the digital dummy model that was created in the previous study (Yamamoto et al., 2015) was used. The digital data of body surface shape were measured for one active male ski jumper (20years, 1.82m in height, 65kg in weight) using a 3D laser scanner (C9036; Hamamatsu Photonics K.K., Japan). A symmetrical posture was made using the right-half on the body shape. The body was divided into 15 segments (head, upper arms, forearms, hands, thorax, pelvis, thighs, shanks and feet) and given joint mobility with sphere joints. The posture of this digital dummy model can be changed as desired with the in-house software (Fig. 1). Two female ski jumpers participated in this study. Jumper A is the world top-class jumper (17 years, 1.52m in height, 47.0kg in weight). On the other hand, Jumper B was a less-experienced jumper (17 years, 1.66m, 52.4kg). A video camera filmed the takeoff motion on the takeoff table, operating at 300 fps (EX-F1; Casio, Japan), perpendicular to the sagittal plane during the discipline on a jumping hill in Sapporo, Japan (HS=95m) in June 2013. The analysis range of interest was 4.6m before the edge of approach track, approximately 0.2s in time. The joint angles were measured with 2-dementional video analysis (Frame-Dias II; DKH Co.,Ltd., Japan). Then, seven postures during the motion for each subject were constructed with the digital dummy model of full scale. The size of the domain was 11m wide, 24.2m long and 13.2m high. FrontFlowRed/Aero was used as a CFD code (Cheng et al., 2012). Large-Eddy Simulation was used as a turbulence model. Spatial accuracy was 95% c2d + 5% 1st upwind and time integration was Euler implicit (Δt: 1.0 x 10^{-4} s). The boundary conditions were set as below.

- Jumper: log-law
- Inlet: U_∞ = 23.23 m/s (83.6km/h)
- Walls: free-slip
- Outlet: open air condition
- Floor: log-law, velocity of 23.23 m/s

Figure 1: The 3D digital dummy model with joint mobility that was made and used in this study

RESULTS: The distribution of airflow speed around the model were showed in Fig. 2. The temporal changes of aerodynamic characters acted upon ski jumper were shown in Fig. 3. Drag force increases sharply as the jumper stands up (Fig.3(a)). Even though the trends were similar for both jumpers, the variation tendency was not the same. In jumper A's case, there was a gradual increase in the first half and then, for the last four postures, a linear sharp one. On the other hand, jumper B's drag increased progressively in a moderate way, and then increase showed a decrease for the last posture. The drag force acting upon jumper B was over twice as much, at the maximum point (-0.075s), than that of jumper A. Jumper A's drag remains lower than Jumper B's during the whole movement. As for the lift force, jumper B's lift was higher than jumper A's at the beginning, because standing positions were more advantageous for lift force (Fig.3(b)). However, after an increase, the B's curve reached a peak at -0.025s and decreased slightly for the last two positions. In Jumper A's case, lift force increased rapidly in the second part of takeoff. Thus, the B's final lift increase was not as high as A's.

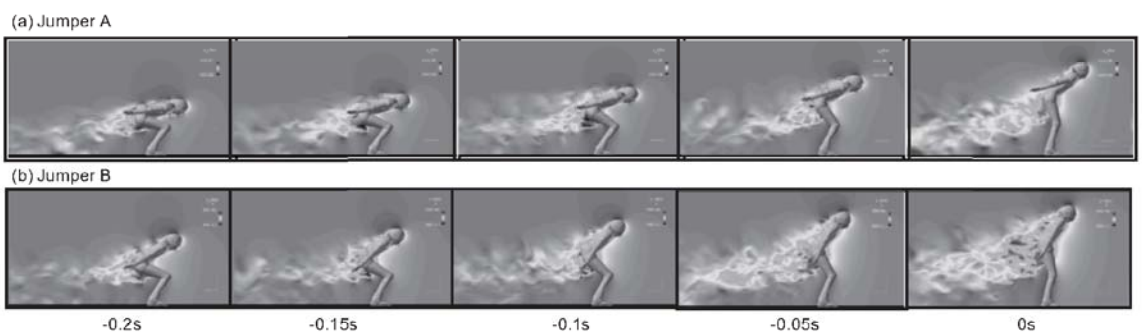

Figure 2: The distribution of airflow speed around the models. Time zero means the moment of takeoff.

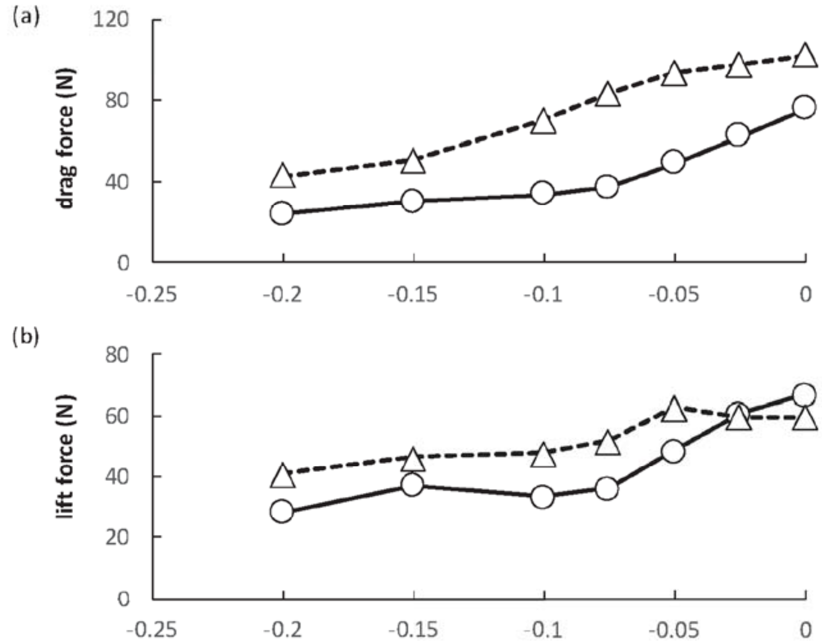

Figure 3: The temporal changes of aerodynamic characters during takeoff. Time zero means the moment of takeoff. Circle represents Jumper A (world-class jumper) and triangle represents Jumper B (less-experienced jumper).

DISCUSSION: The aerodynamic forces acted upon a model in the in-run posture obtained in the present study were similar to those obtained in Virmavirta (2001). They reported the aerodynamic forces acted upon a ski jumper in the wind-tunnel experiment on the condition of $27ms^{-1}$ of the air speed. The drag force varied between 39.2 and 59.7N, and lift force varied between 5.2 and 50.4N. In this study, the drag was 24.1N for jumper A and 42.6N for Jumper B, the lift was 28.4N (A), 40.9N (B) in the in-run posture (Fig. 3). From these results, the validity of the calculation result of CFD was confirmed. Those results also show that the difference in slight posture in the in-run posture has a great influence on the aerodynamics.

The reason why the drag force acted upon the jumper B over that upon jumper A was considered by the attacking angle of trunk. This angle of jumper B was obviously higher than that of jumper A (Fig. 2). The large area of lower air speed behind the jumper B was observed at the end of the motion (Fig. 2(b)). The size of the area would be a factor of the pressure drag force acted upon a jumper because this area represents the stagnant poll of air. The excessive standing position of the trunk causes separation of air flow in the rear of the head, as a result, it is thought that this low-velocity area was formed and increased pressure drag.

Although the lift force of jumper B was larger than that of jumper A in the in-run posture, those two values were reserved for just before the takeoff. Then, the lift of jumper B decreased slightly in the last two postures. It is thought that jumper B caused a stall. Virmavirta et al. (2001) reported A good lift-assisted take-off helps the jumper to obtain a proper flight position (forward leaning) right after takeoff. Schmöltzer et al. (2002) reported that the lift force gradually increases in the early flight phases after the takeoff. It is thought that aerodynamic characteristics in the flight phase would be in a disadvantageous situation when a stall occurs like a jumper B.

Regarding the analysis of flow field, two distinct vortexes generated by the arms produced a downwash flow in the wake of jumper A. A rapid increase of the lift was confirmed for the same period. In jumper B's case, the vortexes coming from the arms were quite distinguishable in the first positions, but later on, those vortexes became disordered. The lift decreased slightly at that point (Fig. 3(b)). It is considered that the positioning of the arms in a very low position like jumper B's motion strongly influences the flow structure. Jumper B's hands are always very near her thighs, and big disordered vortexes are generated that remain during the whole motion. These results suggest that the vortexes generated by the arms seem to be very important for the aerodynamic lift generation as well as the trunk position.

CONCLUSION: The aerodynamic characteristics changed dynamically in a short period during the takeoff motion. The aerodynamics of jumper A (world top-class) were superior to that of jumper B (less-experienced). The drag force acting upon Jumper B was more than 2 times of that of jumper A. The lift force acting upon jumper A increased rapidly right before the takeoff. The excessive rise of the trunk affects the pressure drag because of it generating the vortexes in the wake. Two distinct symmetric vortexes made with the arms produce a downwash flow behind the jumper. The movement of the arms seems to have an influence on generating the lift force. Although the aerodynamic lift acted upon the jumper B was more than that of jumper A in the first half of the motion, the lift peaked during the motion and then decreased slightly at the last two postures. That was regarded as an aerodynamic disadvantage. The aerodynamic strategy already begins with takeoff phase.

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