ANALYSIS OF STABLE FLIGHT IN SKI JUMPING BASED ON PARAMETERS MEASURED WITH A WEARABLE SYSTEM

Julien Chardonnens[1], Julien Favre[1], Florian Cuendet[2], Gérald Gremion[3] and Kamiar Aminian[1]

Laboratory of Movement Analysis and Measurement, EPFL, Lausanne, Switzerland[1]
Swiss-Ski, Bern, Switzerland[2]
Swiss Olympic Center, CHUV, Lausanne, Switzerland[3]

Biomechanics analysis of the ski jump is highly required. Some parameters and their interrelations have been reported in previous research studies limited to few athletes. The generalization of these parameters to athletes of various levels and under training conditions should be assessed, since they have the potential to be used for daily evaluation. This study proposed a new 3D approach based on inertial sensors to evaluate relevant kinematic and aerodynamic parameters of stable flight phase. The proposed wearable system can easily be used for daily training. Aerodynamic forces and body segments 3D angles were extracted during the stable flight phase of 86 jumps. Then, their correlations with respect to distance as well as their interrelations were analyzed. Their combination expressed 55% of the total distance variance.

KEYWORDS: Ski jump, inertial sensors, daily training, angles and aerodynamics, stable flight

INTRODUCTION: In ski jumping, the performance, which is scored by the jump length and style points, is influenced by the athlete movement during all the phases of the jump (i.e., in-run, take-off, early-flight, stable flight and landing). Several studies were conducted to identify measurable parameters that could be related to the performance (Schwameder, 2008). For example, Arndt et al. (1995), Müller et al. (1996) and Schmölzer and Müller (2005) proposed kinematic (e.g., joint angles and V-opening angles) and aerodynamic (e.g., drag and lift forces) parameters during stable flight. Three-dimensional (3D) optical-based capture systems were used to measure these parameters. However, these systems have a small capture volume, need a constraintful calibration and require complex data post-processing. Therefore, these measureable parameters were mainly studied in the frame of specific research applications with few athletes. It is thus necessary to determine if these observations are generalizable to wider population under daily training conditions.
Recently, body worn inertial sensors were proposed to study ski jumping. These small and lightweight devices are not constrained to a limited capture volume and do not require complex post-processing. They are therefore very promising instrumentation for routine in-field measurement of movement in order to provide real-time feedback to the athletes and coaches. However, currently in ski jumping this technology has only been used to extract drag and lift forces (Oghi et al., 2008) and to determine timing events (Aminian et al., 2009).
The first objective of this study was to propose a new easy-to-use method based on body worn inertial sensors to measure the movement during the entire ski jump. This method automatically calculates the timing events, the orientation (3D) of main body segments during the complete jump and the drag and lift forces during stable flight. The second objective was to analyze the correlations of previously suggested parameters with the jump length, as well as their interrelations during the stable flight phase.

METHOD: The measurement system was composed of seven wireless inertial-based modules (Physilog®, BioAGM, CH). Five modules were attached to the athlete by an underwear suit. These modules were located on the sacrum, laterally at the middle length of the thighs and at the middle length of the tibia shaft. The two other modules were fixed on the skis behind the back fixation. Each module, weighting less than 100g, was composed of a 3D gyroscope (±1200 °/s), a 3D accelerometer (±10g) and an embedded datalogger recording the signals at 500 Hz.

32 male athletes (19±4 years old, 173± 8cm, 58±8 kg) from Swiss ski jumping team, including juniors, Nordic combined world-class and world-class athletes, were enrolled in this study. They were asked to perform up to three jumps with the proposed wearable system in K105 hill jump in Einsiedeln (Switzerland) during summer season. Before each jump a calibration procedure was realized to align the inertial modules with the body segments as proposed in Favre et al. (2009). Standard video camera, synchronized with the wearable system, was recorded at 25Hz. Starting platform height, wind conditions, distance and professional evaluation of style were collected for each jump. A score based on distance and starting platform height was calculated for each jump.
To measure body segments orientations and aerodynamic forces, the following steps were performed. First, some temporal features (i.e., take-off, beginning of stable flight, end of stable flight and landing impact) were detected by identifying specific features in the inertial signals (Aminian et al., 2008). Then, based on the acceleration signals measured during in-run phase, an initial orientation was defined for each body segment. An algorithm fusing the angular velocities, accelerations and aerodynamic constraints was then used to calculate the segments orientations until landing (Bortz, 1971). Finally, aerodynamic forces were evaluated during stable flight phase applying the first Newton law to the sacrum acceleration. Using the sacrum orientation, these forces were projected in the jumping hill reception frame X'Y'Z' (see Fig.1), where X' and Z' corresponded respectively to drag and lift forces.
To date, several parameters of the stable flight were analyzed (Arndt et al., 1995; Müller et al., 1996; Schmölzer and Müller, 2005). However for shake of consistency, only a subset was considered in this study. Moreover, some literature parameters were adapted because the wearable system did not measure the trajectory. These parameters are described below and in Fig. 1a and Fig. 1b. 1) Median of ski angle α with respect to horizontal in sagittal plane. This angle was used instead of the angle of attack. 2) Median of angle β between ski and shank in sagittal plane. 3) Median of angle γ between thigh and sacrum in sagittal plane. 4) Medians of V-angles V_f and V_t between skis in frontal and transverse planes. This decomposition allowed a 3D description of skis angles. 5) Medians and differences between 5th and 95th percentiles of sacrum drag and lift forces F_d and F_l. For the lower limbs, the values of the left and right sides were averaged:

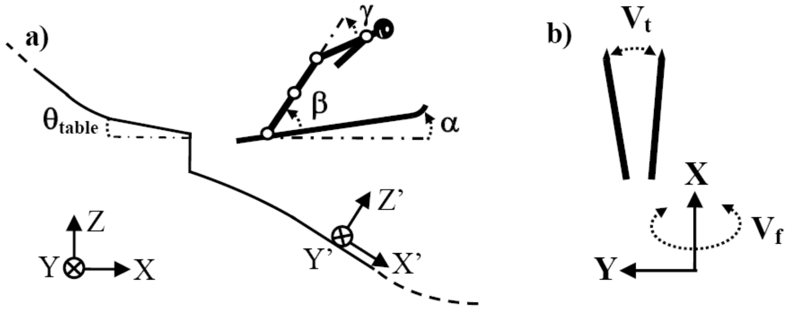

Figure 1. a) In sagittal plane, ski-horizontal angle (α), ski-shank angle (β), thigh-sacrum angle (γ) and representation of XYZ and X'Y'Z' frames corresponding respectively to jumping hill frame and jumping hill reception frame. b) V-angle between skis expressed in transverse plane (V_t) and in frontal plane (V_f).

Finally, the correlations between the extracted parameters and the distance score, as well as the correlations between the extracted parameters were evaluated based on Pearson linear method. P-values were also calculated to estimate the level of significance.

RESULTS: Body segments orientations and aerodynamic forces were reconstructed for a total of 86 jumps. Typical angles, as well as drag and lift forces curves are shown in Fig. 2. Correlations relative to distance score and between parameters are presented in Table 1. In addition, multiple regression analysis showed that the combination of all extracted parameters explained 55% (r=0.74) of the variance of distance score. For comparison, the angular parameters (α,β,γ,V_f and V_t) and forces parameters (F_d and F_l) explained respectively 42% (r=0.65) and 49% (r=0.70) of the variance of distance score.

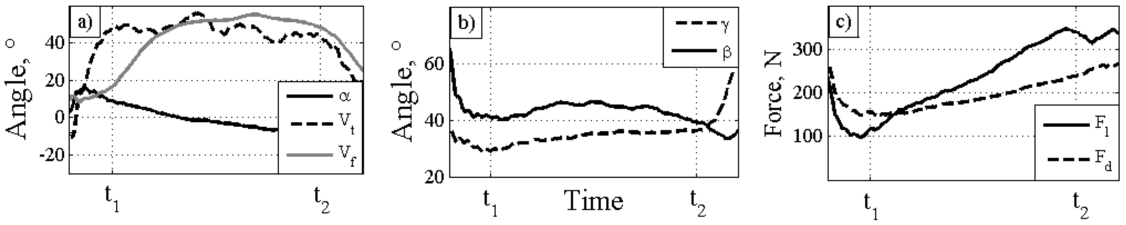

Figure 2. Kimatic and aerodynamic curves for a typical jump of a world-class athlete. t_1 and t_2 correpond to the beginning and to the end of the stable flight phase.

Table 1. Correlation coefficient r between each parameter and distance score

N=86		α	β	γ	V_f	V_t	F_d		F_l	
		MED	MED	MED	MED	MED	MED	PCTILE	MED	PCTILE
Distance score		**−0.45*** **	−0.24*	*NS*	**0.53*** **	0.26*	**0.31** **	**0.31** **	**0.62*** **	**0.57*** **
α	MED		**0.41*** **	*NS*	**-0.43*** **	*NS*	*NS*	*NS*	**-0.44*** **	**-0.60*** **
β	MED			*NS*	**-0.31** **	**-0.51*** **	*NS*	*NS*	*NS*	*NS*
γ	MED				*NS*	*NS*	*NS*	*NS*	*NS*	-0.25*
V_f	MED					**0.32** **	0.25*	*NS*	**0.62*** **	**0.41*** **
V_t	MED						**0.47*** **	**0.28** **	*NS*	NS
F_d	MED							*NS*	**0.46*** **	NS
	PCTILE								*NS*	**0.39*** **
F_l	MED									**0.54*** **

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; *NS* $p>0.05$

DISCUSSION: The inertial-based method presented in this study allowed measuring body segments orientations during the entire jump sequence and aerodynamics during stable flight. It also allowed an automatic extraction of angular and force parameters. Finally, this method did not alter the movement and could be used in daily training conditions. Generally the angles and forces curves (Fig. 2) obtained through this inertial-based system were in accordance to those in literature (Schmölzer and Müller, 2005). But we found slightly larger ski-shank angle curve β and V-opening angle curve V_t.

Regarding the aerodynamics, our results showed a good correlation between the distance score and the lift force F_l. Indeed, the correlations were positive for both the median value (r=0.62) and the increase (r=0.57) of F_l during stable flight. This could mirror an augmentation of velocity during flight and a proper aerodynamic posture. It was observed that the drag force F_d increased with lift force F_l. We hypothesized that this was due to a velocity increase. Schmölzer and Müller (2005) reported that the drag force augmentation has a minor negative effect on distance. In our study, both F_l and F_d were positively correlated with the distance. On the other hand, Müller et al. (1996) suggested to maximize the lift to drag force ratio. This suggestion was not supported in our study, where the lift to drag force ratio reported only a correlation of 0.36 with the distance. But, these statements should be considered with caution, since F_d and F_l were expressed in X'Y'Z' frame.

Regarding the body segments and skis kinematics, two parameters were highlighted with respect to distance: the ski angle α with repsect to horizontzal (r=-0.45) and the V-opening angle in the frontal plane V_f (r=0.53). When estimating the correlation by combining all angular parameters with respect to distance score, a total correlation of 0.65 was obtained. This indicates that the angle parameters were correlated to each other as illustrated in table 1. The ski-shank angle β was weakly correlated with the performance (r=-0.24), which differed a little from literature (Schmölzer and Müller, 2005; Schwameder, 2008). Except for a low correlation with lift force F_l, the sacrum-thigh angle γ did not show any significant correlation. Although the γ angle varied between athletes, it was not related to the performance. As mentioned by Müller et al. (1996) and Schwameder (2008), the V-technique allows reaching low ski-horizontal angle α (-0.43) and ski-shank angle β (r=-0.51). Furthermore, a high V_f, low α and low β suggested a more efficient flight posture, as indicated by their correlation with the lift force. Schwameder (2008) mentioned that the angle formed between skis was related to jump length. However, in our study, only V_f (influencing the distance between skis) showed an acceptable correlation with distance score. This was also reported by Arndt et al. (1995), since he found that the distance between skis was more relevant than the angle between them.

It is interesting to note that the parameters that athletes actually control during stable flight (α,β,γ,V_f and V_t) reported a good total correlation (r=0.65) with the distance score. The aerodynamic parameters (F_d and F_l) showed a similar correlation with distance (r=0.7). However, when considering all parameters the correlation only slightly increased (r=0.74). This suggests that force and angular parameters are correlated, as confirmed in Table 1. Indeed, drag and lift forces would be a part of the result of an aerodynamic posture.

CONCLUSION: In general, the correlations obtained on a large cohort during this study agreed with literature (Arndt et al., 1995; Schmölzer and Müller, 2005, Schwameder, 2008), where video cameras were used. Especially, the relevance of ski-horizontal angle α, V-opening angle V_f in frontal plane and lift force F_l was highlighted in regard to distance. But, ski-shank angle β and V-opening angle V_t were found weakly related to performance. It was the first time that skis kinematics during flight was described in 3D by considering α,V_t and V_f. Compared to previous studies, we had large differences of jumpers level. It is worth mentioning that by considering these nine parameters (all measured during the stable flight), 55% (r^2) of the whole variance of the distance score could be expressed. The analysis of the correlations between the proposed parameters improved the understanding of their interrelations. The inclusion of additional parameters (e.g., wind, in-run speed) would certainly improve the analysis. Finally, previous studies have shown that take-off and early-flight phases were also highly related to the performance (Arndt et al., 1995, Schwameder, 2008). Indeed they have a direct influence on the dynamics and kinematics reached in stable flight phase. The method proposed in this study could easily be extended to analyze the take-off and early-flight phases as well. Therefore, we can conclude that this inertial-based approach has a high potential for measuring and guiding ski jumpers during daily training.

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