

Aerodynamic characteristics of effective early flight postures for ski jumping: Exploratory CFD analysis

Tomoya Ueno

tomo.quick1997@gmail.com

Hokusho University

Shimpei Hatano

Kobe University

Tokimasa Shimada

Kobe University

Rahul Bale

RIKEN Advanced Institute for Computational Science

Keizo Yamamoto

Hokusho University

Makoto Tsubokura

Kobe University

Research Article

Keywords: Computational fluid dynamics, drag, flight style, lift, unsteady flow

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11288162/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

This study was conducted to clarify the aerodynamic characteristics of representative trials selected from movement-strategy clusters during the early flight phase of ski jumping, as identified in recent work by the author and others. An earlier study identified three movement-strategy clusters based on trunk, hip, and knee joint coordination patterns. For the present study, after one representative trial was selected from each cluster, it was analysed using unsteady computational fluid dynamics. The selected trials were designated as Jumper A (Cluster 1), Jumper B (Cluster 2), and Jumper C (Cluster 3). All trials exceeded the hill's construction point (K-point, $K = 90$ m). Despite achieving high-level performance, the representative trials exhibited distinct aerodynamic profiles. Jumper A showed a drag-reduction profile characterised by low drag, a more attached flow field, and the highest lift-to-drag ratio during late early flight. Jumper B showed a lift-oriented profile characterised by rapid lift acquisition and greater wake development. Jumper C showed a balanced profile characterised by gradual aerodynamic-force development and moderate wake formation. These findings suggest that different early flight movement strategies might correspond to distinct aerodynamic solutions. This study provides preliminary CFD analysis-based evidence linking movement strategies and aerodynamic characteristics during the early flight phase.

Introduction

For biomechanical analyses, a ski jump is typically divided into six phases: in-run, take-off, early flight, stable flight, landing preparation, and landing [1–3]. The early flight phase extends from leaving the take-off table until the lift-to-drag ratio (L/D) reaches a steady state [2, 4]. During this phase, the jumper must achieve stable flight as quickly as possible [1, 2]. Previous studies have examined early flight posture changes primarily from either kinematic [2, 5–10] or aerodynamic perspectives [3, 11–14].

From a kinematic perspective, coordination of the trunk, hip, and knee joints plays an important role in early flight posture formation and might influence both jump distance and aerodynamic characteristics [2]. However, previous studies have often relied on group-based comparisons, such as skill level or age, potentially overlooking diverse movement strategies among jumpers with similar performance levels [6, 15]. To address this limitation, Ueno et al. [2] applied principal component analysis to time-series waveforms of trunk, hip, and knee joint angles and subsequently classified the resulting principal component scores. They identified three distinct movement strategies based on joint-coordination patterns. Although all analysed trials achieved high-level performance ($\geq K$ -point, $K = 90$ m), the strategies differed significantly in their kinematic characteristics. However, because these strategies were identified solely from kinematic data, their aerodynamic characteristics remain unknown.

From an aerodynamic perspective, computational fluid dynamics (CFD) studies have demonstrated that posture strongly influences aerodynamic forces during early flight. Gardan et al. [12] showed that variations in angle of attack affect the lift and drag acting on a ski jumper, although their analysis was limited to steady-state postures. Using unsteady CFD, Yamamoto et al. [3] demonstrated that lift and

drag increase rapidly immediately after take-off, followed by a reduction in drag as the jumper transitions to stable flight, with corresponding changes in wake development. They also reported that expert jumpers transitioned more rapidly to aerodynamically advantageous postures and exhibited higher L/D values during early flight. Other studies suggest that successful flight might be achieved through multiple aerodynamic solutions. Ski jumpers must balance force generation to reduce vertical descent velocity against drag reduction to preserve horizontal velocity [4], while postures that maximise peak lift do not necessarily maximise L/D [16]. Furthermore, elite jumpers achieving similar distances might employ different aerodynamic strategies [17]. Nevertheless, previous aerodynamic studies have focused mainly on skill-level comparisons or isolated postural characteristics and have not established whether kinematically identified movement strategies correspond to distinct aerodynamic mechanisms.

This study investigated the aerodynamic characteristics associated with different movement strategies during the early flight phase of ski jumping. Exploratory CFD analyses were conducted on representative trials selected from the movement-strategy clusters identified by Ueno et al. [2]. We hypothesised that trials representing different clusters would exhibit distinct aerodynamic profiles despite all achieving high-level performance. By extending the kinematic findings of Ueno et al. [2] into the aerodynamic domain, this study provides preliminary insight into how different movement strategies might be associated with aerodynamic performance and offers practical implications for coaches and jumpers during the transition from take-off to stable flight.

Methods

Kinematic dataset

The kinematic data used for this study were obtained from a dataset published earlier [2], for which early flight postures in ski jumping were classified into distinct movement strategy clusters. For the present study, the authors utilised both the kinematic dataset and the corresponding clustering results for subsequent CFD analysis. Detailed descriptions of participant characteristics, data acquisition, signal processing, and statistical analysis procedures were provided earlier by Ueno et al. [2]. The relevant institutional ethics committee (HOKUSHO-UNIV: 2024-013) reviewed and approved the study protocol.

Selection of representative trials from each cluster

One representative expert jumper was selected from each of the three movement-strategy clusters identified by Ueno et al. [2] for exploratory CFD analysis. Cluster 1 exhibited trunk and knee joint kinematics similar to those of Cluster 2, but a distinct hip-joint trajectory that began in an intermediate flexed position and gradually converged toward the Cluster 3 posture during the latter part of early flight. Cluster 2 was characterised by a relatively upright trunk and rapid hip and knee extension immediately after take-off, whereas Cluster 3 exhibited a flatter trunk and greater hip and knee flexion, followed by more gradual extension. The selected athletes were designated Jumper A (Cluster 1), Jumper B (Cluster

2), and Jumper C (Cluster 3). All were members of the Japanese national ski jumping team, competed at the 2026 Milano–Cortina Winter Olympic Games, and exceeded the K-point in the selected trials. Their characteristics at data collection were Jumper A, 167.0 cm, 57.6 kg, 22 years, male; Jumper B, 174.0 cm, 62.0 kg, 27 years, male; and Jumper C, 161.0 cm, 47.8 kg, 29 years, female.

CFD workflow

A posture-variant CFD workflow based on Yamamoto et al. [3] integrated markerless motion-capture data with a three-dimensional geometric model of a ski jumper. A whole-body model was constructed from surface-geometry data, and the same scaled body-surface model was used for all jumpers, with only joint kinematics differing among jumpers. Kinematic data from each representative trial were mapped onto the model to reproduce jumper-specific posture changes throughout early flight. The resulting posture-variant models were incorporated into unsteady CFD simulations to quantify temporal changes in aerodynamic forces and flow fields. This approach combined a scaled generic body geometry with jumper-specific kinematics to investigate the aerodynamic consequences of different movement strategies.

CFD framework and computational setup

The early flight phase comprised the 0.2 s immediately following take-off [2], during which prescribed postural changes were reproduced. To reduce the computational cost associated with the jumper's approximately 4 m displacement, the flow was solved in a non-inertial frame translating with the jumper, assuming rigid-body translation without rotation. The incompressible Navier–Stokes and continuity equations were coupled to prescribed deformation using an immersed-boundary formulation. Time integration used a fractional-step method [18] with Crank–Nicolson discretisation. QUICK and second-order central-difference schemes were applied to advection and diffusion, respectively; QUICK dissipation provided implicit large-eddy modelling [19, 20]. The CFD simulations were performed using the in-house massively parallel flow solver CUBE [18], employing the building cube method for Cartesian grid generation [21] and an immersed-boundary method for representing complex geometries [22, 23]. The numerical methodology and computational setup were adapted from Yamamoto et al. [3]. In that study, although the CFD framework underestimated the absolute magnitudes of lift and drag, it reproduced their temporal trends and the L/D obtained from Global Navigation Satellite System (GNSS)-based estimates, supporting its application to comparative aerodynamic analyses. All simulations shared the domain and boundary conditions, with trial-specific grid refinement. The domain maintained a blockage ratio below 2%, with the jumper positioned centrally. Prescribed postural motion was reproduced, whereas translation was represented by an inflow vector ($U_x, 0, U_z$). Further details are provided in Supplementary Information S1–S3.

Aerodynamic variables

Aerodynamic performance was evaluated using lift, drag, and the L/D. These variables were obtained by integrating the pressure and viscous (shear) stresses over the body surface, as defined below. Time-series changes in aerodynamic forces during the early flight phase were analysed.

Calculation of aerodynamic forces

The total aerodynamic force acting on the jumper, $\mathbf{F}$, is obtained by integrating the surface traction over the body surface S as

$$\mathbf{F} = \oint_S \boldsymbol{\sigma} \cdot \mathbf{n} dS = \oint_S (-p \mathbf{n} + \boldsymbol{\tau} \cdot \mathbf{n}) dS \quad (1)$$

where $\mathbf{n}$ denotes the outward unit normal on the body surface, $\boldsymbol{\sigma} = -p \mathbf{I} + \boldsymbol{\tau}$ is the stress tensor, and $\boldsymbol{\tau} = \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$ is the viscous stress tensor for an incompressible Newtonian fluid. The integral is evaluated as a discrete sum of the pressure and viscous-stress contributions over the surface elements.

Lift and drag are defined relative to the prescribed inflow (relative-wind) direction. With the inflow velocity vector $\mathbf{U}_{in} = (U_x, 0, U_z)$, the drag and lift unit vectors are $\mathbf{e}_D = \mathbf{U}_{in} / |\mathbf{U}_{in}|$ (parallel to the inflow) and $\mathbf{e}_L$ (perpendicular to $\mathbf{U}_{in}$ in the vertical plane). Drag and lift are the corresponding components of $\mathbf{F}$.

$$D = \mathbf{F} \cdot \mathbf{e}_D, \quad L = \mathbf{F} \cdot \mathbf{e}_L \quad (2)$$

Also, the lift-to-drag ratio is given by L/D .

Results

Validation of representative trials for CFD analysis

To verify that the selected trials represented their respective movement strategies, their trunk, hip, and knee joint principal component (PC) scores were mapped onto the cluster distributions reported by Ueno et al. [2]. All representative trials were within the interquartile ranges of their respective clusters and were not outliers, supporting their suitability for exploratory aerodynamic evaluation. Figure 1a presents temporal changes in lift, drag, and L/D, whereas Fig. 1b shows the corresponding airflow visualisations. Although all selected trials exceeded the K-point, they exhibited distinctly different aerodynamic characteristics.

Aerodynamic profile of Jumper A

Jumper A exhibited the lowest lift values throughout the analysed period. Lift increased gradually from approximately 40 N at take-off to approximately 80 N at 0.2 s after take-off, but it remained lower than that observed for either Jumper B or Jumper C throughout the early flight phase (Fig. 1a, top). Drag also remained consistently lower than that observed for either Jumper B or Jumper C, ranging between approximately 60 N and 80 N from take-off to 0.2 s after take-off (Fig. 1a, middle). Consequently, the L/D of Jumper A increased progressively after take-off and became the highest among the three jumpers at

approximately 0.15 s after take-off (Fig. 1a, bottom). The streamline visualizations in Fig. 1b (top) revealed a smooth airflow pattern around the jumper throughout the early flight phase. Immediately after take-off, streamlines remained largely attached to the body and ski surfaces. Only a small wake region was observed behind the athlete. At 0.1 s after take-off, wake development remained limited, with only a narrow region of disturbed streamlines visible behind the jumper. By 0.2 s after take-off, the wake region had increased slightly. However, it remained smaller than that observed for either Jumper B or Jumper C. Compared with Jumpers B and C, the flow field behind the jumper exhibited a smaller region of disturbed streamlines and less apparent flow separation throughout the analysed period. Furthermore, only limited evidence of recirculating flow was observed immediately behind the body, reflecting a stable wake structure. Taken together, these aerodynamic characteristics suggest that Jumper A exhibited a drag-reduction-oriented aerodynamic profile during the early flight phase.

Aerodynamic profile of Jumper B

Jumper B exhibited the highest lift values throughout the analysed period. Lift increased from approximately 50 N at take-off to approximately 100 N at 0.2 s after take-off. Thereafter, lift remained greater than that observed for either Jumper A or Jumper C during most of the early flight phase (Fig. 1a, top). Drag, which was approximately 100 N immediately after take-off, increased gradually during the first 0.1 s of flight. After reaching its peak at approximately 0.1 s after take-off, drag decreased and remained between the values observed for Jumpers A and C during the remainder of the analysed period (Fig. 1a, middle). Consequently, the L/D increased progressively from approximately 0.5 at take-off to approximately 0.8 at 0.2 s after take-off (Fig. 1a, bottom). The streamline visualizations in Fig. 1b (middle) revealed a large wake region behind the jumper throughout the early flight phase. This wake region, which was already evident immediately after take-off, expanded further between 0.1 and 0.2 s after take-off. Compared with Jumpers A and C, the flow field behind the jumper exhibited a broader region of disturbed streamlines and more pronounced flow separation. Furthermore, regions of recirculating flow were observed immediately behind the body, indicating a complex wake structure throughout the analysed period. Taken together, these aerodynamic characteristics suggest that Jumper B exhibited a lift-acquisition-oriented aerodynamic profile during the early flight phase.

Aerodynamic profile of Jumper C

Jumper C exhibited lift values that were generally intermediate between those observed for Jumpers A and B throughout the analysed period. Lift increased from approximately 30 N at take-off to approximately 100 N at 0.2 s after take-off and remained greater than that observed for Jumper A but lower than that observed for Jumper B during most of the early flight phase (Fig. 1a, top). Drag increased rapidly during the 0.1 s after take-off and subsequently remained stable at approximately 120 N throughout the remainder of the analysed period (Fig. 1a, middle). Consequently, the L/D increased progressively from approximately 0.3 at take-off to approximately 0.7 at 0.2 s after take-off (Fig. 1a, bottom). Although the L/D remained lower than that observed for Jumpers A and B during the early flight phase, the differences among the jumpers became smaller toward the end of the analysed period. The streamline visualizations in Fig. 1b (bottom) revealed a wake region behind the jumper that was larger

than that observed for Jumper A but generally smaller than that observed for Jumper B. Immediately after take-off, a moderate wake region was already visible behind the body. Between 0.05 s and 0.15 s after take-off, the wake expanded gradually, accompanied by an increasing region of disturbed streamlines behind the jumper. By 0.2 s after take-off, the wake structure had become more pronounced. However, the extent of flow disturbance remained less than that observed for Jumper B. Compared with Jumper B, the flow field behind the jumper exhibited less apparent flow separation and a smaller region of recirculating flow throughout the analysed period. These observations indicate that Jumper C generated aerodynamic forces without exhibiting the extensive wake development observed for Jumper B. Taken together, these aerodynamic characteristics suggest that Jumper C exhibited a balanced aerodynamic profile during the early flight phase, characterised by moderate lift generation and moderate drag production.

Discussion

This study using unsteady CFD analysis was undertaken primarily to clarify aerodynamic characteristics associated with the three effective movement strategies during the early flight phase of ski jumping, which were identified previously by Ueno et al. [2]. The results demonstrated that the three jumpers, all achieving high-level performance, reached these outcomes through distinctly different aerodynamic characteristics. Specifically, the three jumpers exhibited a drag-reduction profile (Jumper A), a lift-oriented profile (Jumper B), and a balanced profile (Jumper C).

Aerodynamic interpretation of Jumper A

Ueno et al. [2] reported that jumpers classified into Cluster 1 exhibited trunk and knee movement patterns that closely resembled those observed in Cluster 2, whereas hip-joint movements followed a distinct trajectory. Specifically, the hip joint started from an intermediate flexed position and converged gradually toward the posture observed in Cluster 3 during the latter part of the early flight phase. The flow visualisations revealed limited wake development and less pronounced flow separation than those observed for Jumper B. Jumper A maintained a compact wake region and exhibited a smaller area of disturbed streamlines behind the body and skis, which might have contributed to the lower drag observed throughout the early flight phase while allowing lift to increase progressively over time. Among the three kinematic variables examined by Ueno et al. [2], hip-joint movement was identified as the primary characteristic distinguishing Cluster 1 from Cluster 2. The contrasting aerodynamic profiles therefore raise the possibility that hip-joint movement influences wake development and drag regulation. Although causal relations cannot be established from the present data, the findings suggest that subtle differences in movement coordination are associated with meaningful differences in the surrounding flow field. Previous studies have associated posture-dependent changes in wake formation, flow separation, and drag with preservation of horizontal velocity and favourable aerodynamic performance [7, 12, 14, 16]. Consistent with the different aerodynamic strategies proposed by Jølstad et al. [17], Jumper A might represent an aerodynamic pathway characterised by low drag and a high L/D, potentially facilitating the preservation of horizontal velocity during the early flight phase.

Aerodynamic interpretation of Jumper B

Ueno et al. [2] reported that jumpers classified into Cluster 2 generally exhibited a rising trunk posture combined with rapid extension of the hip and knee joints, leading to an earlier transition toward a more extended whole-body configuration. Results of CFD analysis revealed rapid increases in both lift and drag immediately after take-off and demonstrated the greatest lift generation among the three jumpers. Flow visualisations revealed a large wake region, pronounced flow separation, and recirculating flow immediately downstream of the body. Although the present analysis accommodates no direct inference related to all jumpers within Cluster 2, these characteristics appear to be broadly compatible with the movement strategy reported by Ueno et al. [2]. The earlier transition toward an extended whole-body posture might increase the effective area exposed to the airflow, thereby promoting rapid lift generation while simultaneously increasing pressure drag. Earlier CFD studies have suggested that body extension during take-off influences aerodynamic force generation and the surrounding flow field [24]. Thus, Jumper B might reflect an aerodynamic trade-off by which rapid lift acquisition is achieved at the cost of increased wake formation, momentum loss, and aerodynamic losses. This interpretation is consistent with Yamamoto et al. [3], who demonstrated that rapid adoption of an extended posture led to sharp increases in both lift and drag and a rapid rise in L/D . Because strong aerodynamic forces might help reduce vertical descent velocity [4, 17], Jumper B might represent an aerodynamic solution that prioritizes early aerodynamic force production despite the associated increase in wake development and aerodynamic losses.

Aerodynamic interpretation of Jumper C

Ueno et al. [2] reported that jumpers classified into Cluster 3 exhibited a flatter trunk posture and more gradual extension of the hip and knee joints, maintaining a more flexed lower-limb posture immediately after take-off. Results of CFD analysis demonstrated gradual increases in both lift and drag, without the pronounced force peaks and extensive wake development observed for Jumper B or the marked drag reduction observed for Jumper A. Flow visualisations revealed moderate wake development, with flow disturbances that were less pronounced than those observed for Jumper B but more evident than those observed for Jumper A. Consequently, Jumper C appeared to occupy an intermediate aerodynamic state between the lift-oriented profile of Jumper B and the drag-reduction-oriented profile of Jumper A. Previous studies have suggested that a compact flight posture contributes to the development of favourable aerodynamic conditions [8, 9], whereas flow separation and wake development contribute to increased drag [12]. The absence of abrupt posture changes in Jumper C might therefore have limited excessive wake growth and contributed to the gradual and stable development of aerodynamic forces. Taken together, Jumper C might illustrate an aerodynamic pathway characterised by a gradual balance between lift generation and drag suppression. Taken together, the distinct aerodynamic profiles of Jumpers A–C suggest that successful early flight performance might be achieved through different solutions to the trade-off between force generation and drag suppression. Thus, the movement-strategy diversity identified by Ueno et al. [2] might reflect not only kinematic variation but also different approaches to managing the aerodynamic demands of early flight.

Several limitations must be acknowledged. First, because of the considerable computational cost associated with unsteady CFD simulations, only one representative trial from each cluster was analysed. Consequently, this study was inadequate for comprehensive evaluation of the influences of confounding factors such as inter-individual differences in body morphology, sex, equipment characteristics, and subtle variations in kinematics within each cluster. Furthermore, statistical comparisons of aerodynamic characteristics between clusters could not be performed. Therefore, the distinct aerodynamic profiles identified in this study should be interpreted as exploratory observations derived from representative elite-level trials rather than as characteristics generalisable to all jumpers within each cluster. Second, although the representative postures were obtained from three elite jumpers, all simulations were performed using a single body-scan model that was scaled to approximate their anthropometric dimensions [3]. Consequently, individual differences in body shape, segment proportions, body-surface geometry, and equipment fit were not reproduced. Because aerodynamic characteristics are influenced by both posture and morphology, some observed differences might reflect limitations associated with the generic body model rather than the true subject-specific aerodynamic characteristics of each athlete. Third, the present study evaluated aerodynamic forces acting on the athlete's body but not those acting on the skis. Although ski geometry was incorporated into the computational model to reproduce realistic flight postures, lift and drag acting on the skis were not quantified. Consequently, the present findings should be interpreted as body-based aerodynamic characteristics rather than as a comprehensive aerodynamic assessment of the entire skier–ski system. Because ski-related factors, including the ski angle of attack, ski-opening angle, and body–ski configuration, strongly influence aerodynamic performance [25–28], the aerodynamic mechanisms identified in this study likely represent only part of the overall aerodynamic characteristics during ski-jumping flight. Fourth, several simplifications were adopted for the CFD framework. The translational motion of the jumper was represented through inflow boundary conditions within a non-inertial reference frame fixed to the athlete, and the coupling between body motion and airflow was unidirectional. Consequently, posture changes influenced the surrounding airflow and aerodynamic-force calculations, whereas aerodynamic forces did not affect body motion during the simulations. In addition, simplifications of the computational domain and boundary conditions might have altered local flow structures relative to actual flight conditions. Therefore, the present simulations should be regarded as an approximation of the aerodynamic environment experienced during the early flight phase. Finally, although the CFD framework was based on that developed and validated by Yamamoto et al. [3], the accuracy of the calculated aerodynamic forces remains influenced by grid resolution, body-surface representation, and boundary-layer modelling. A formal grid-sensitivity analysis was not performed because of the considerable computational cost, and grid independence was therefore not established. Consequently, the absolute magnitudes of lift and drag should be interpreted with caution. Rather than providing exact predictions of aerodynamic forces, the primary value of the present analysis lies in the relative comparison of aerodynamic characteristics among representative movement strategies. Future studies incorporating larger sample sizes, subject-specific body geometries, detailed ski-kinematic analyses, systematic grid-sensitivity analyses with finer spatial resolution, aerodynamic validation experiments, and wind-tunnel measurements are expected to

improve our understanding of how individualised movement strategies influence aerodynamic performance during the early flight phase.

Conclusions

This study was conducted using unsteady CFD analysis to investigate the characteristics of aerodynamics acting on an athlete's body in association with the three effective movement strategies used during the early flight phase of ski jumping identified by Ueno et al. [2]. The analyses yielded the following key insights.

- Distinct aerodynamic profiles were observed among representative trials selected from the three kinematically defined movement-strategy clusters. The representative trials exhibited different temporal patterns of lift, drag, L/D, and wake development during the early flight phase. Specifically, Jumper A exhibited a drag-reduction profile. Jumper B exhibited a lift-oriented profile. Jumper C exhibited a balanced aerodynamic profile.
- Multiple aerodynamic solutions may contribute to successful early flight performance. Although all representative trials achieved high-level performance, they exhibited markedly different aerodynamic characteristics. These findings suggest that jumpers might achieve successful early flight performance through different aerodynamic pathways, such as prioritising drag suppression, rapid aerodynamic-force generation, and stable aerodynamic development.
- The combined use of kinematic classification and unsteady CFD analysis provides a useful framework for investigating the relation between movement strategy and aerodynamic performance. By extending the kinematic classification proposed by Ueno et al. [2] into the aerodynamic domain, the present study provides preliminary CFD analysis-based evidence indicating that different early flight movement strategies might be associated with distinct aerodynamic profiles.

Although the present findings should be interpreted cautiously because the analysis was limited to one representative trial per cluster and because the analysis addressed only those aerodynamic characteristics acting on the athlete's body, this study provides preliminary biomechanical insight into how different movement strategies might influence aerodynamic performance during the early flight phase of ski jumping.

Declarations

Funding

This work was supported by JSPS KAKENHI (JP 25K02996).

Declaration of Interest Statement

The authors have no conflict of interest.

Author Contribution

T.U. analyzed and interpreted the data, prepared the figures, wrote the first draft of the manuscript, and critically revised the manuscript. S.H. performed the simulations and analyzed the data. T.S. performed the simulations, analyzed the data, and supervised the research. R.B. performed the simulations, analyzed the data, prepared the figures, critically revised the manuscript, and supervised the research. K.Y. contributed to the conception and design of the study, supervised the research, acquired funding, and critically revised the manuscript. M.T. contributed to the conception and design of the study and supervised the research. All authors commented on previous versions of the manuscript, read and approved the final manuscript, and agreed to be accountable for all aspects of the work.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available because they contain information that could compromise the privacy of the participants.

References

1. Schwameder H (2008) Biomechanics research in ski jumping, 1991–2006. *Sports Biomech* 7(1):114–136. <https://doi.org/10.1080/14763140701687560>
2. Ueno T, Ishihara T, Yamamoto K (2026) Identification and classification of kinematically effective early flight postures in ski jumping. *Sports Biomech* 1–25. <https://doi.org/10.1080/14763141.2026.2649472>
3. Yamamoto K, Nishino T, Bale R, Shimada T, Miyamoto N, Tsubokura M (2022) Numerical study of transient aerodynamic forces acting on a ski jumper considering dynamic posture change from takeoff to landing. *Sports Biomechanics* 1–15. <https://doi.org/10.1080/14763141.2022.2154256>
4. Elfmark O, Ettema G, Gilgien M (2022) Assessment of the steady glide phase in ski jumping. *J Biomech* 139:111139. <https://doi.org/10.1016/j.jbiomech.2022.111139>
5. Janura M, Cabell L, Svoboda Z, Elfmark M, Janurová E (2011) Analysis of the beginning of the early flight phase of the ski jump in athletes with different performance levels. *Acta Univ Palacki Olomuc Gymnica* 41(3):7–13. <https://doi.org/10.5507/ag.2011.015>
6. Janura M, Cabell L, Svoboda Z, Elfmark M, Zahalka F (2011) Kinematic analysis of the take-off and start of the early flight phase on a large hill (HS-134 m) during the 2009 Nordic world ski championships. *J Hum Kinetics* 27(1):5–16. <https://doi.org/10.2478/v10078-011-0001-5>
7. Schmölzer B, Müller W (2005) Individual flight styles in ski jumping: results obtained during Olympic Games competitions. *J Biomech* 38(5):1055–1065. <https://doi.org/10.1016/j.jbiomech.2004.05.038>
8. Schwameder H, Müller E, Lindenhofner E, DeMonte G, Potthast W, Brüggemann P, Virmaavirta M, Isolehto J, Komi P (2005) Kinematic characteristics of the early flight phase in ski-jumping. *Sci*

9. Virmaavirta M, Isolehto J, Komi P, Brüggemann GP, Müller E, Schwameder H (2005) Characteristics of the early flight phase in the Olympic ski jumping competition. *J Biomech* 38(11):2157–2163. <https://doi.org/10.1016/j.jbiomech.2004.10.004>
10. Yu J, Ma X, Qi S, Liang Z, Wei Z, Li Q, Ni W, Wei S, Zhang S (2023) Key transition technology of ski jumping based on inertial motion unit, kinematics and dynamics. *Biomed Eng Online* 22(1):21. <https://doi.org/10.1186/s12938-023-01087-x>
11. Denoth J, Luethi SM, Gasser HH (1987) Methodological problems in optimization of the flight phase in ski jumping. *J Appl Biomech* 3(4):404–418. <https://doi.org/10.1123/ijsb.3.4.404>
12. Gardan N, Schneider A, Polidori G, Trenchard H, Seigneur JM, Beaumont F, Fourchet F, Taiar R (2017) Numerical investigation of the early flight phase in ski-jumping. *J Biomech* 59:29–34. <http://dx.doi.org/10.1016/j.jbiomech.2017.05.013>
13. Liu K, Wang Z, Liu Q (2025) Numerical Study of the Aerodynamic Effect of Ski Suit Surface Roughness on Ski Jumping Athletes During the Flight Phase. *J Appl Fluid Mech* 18(3):710–727. <https://doi.org/10.47176/jafm.18.3.2871>
14. Seo K, Murakami M, Yoshida K (2004) Optimal flight technique for V-style ski jumping. *Sports Eng* 7(2):97–103. <https://doi.org/10.1007/BF02915921>
15. Virmaavirta M, Isolehto J, Komi P, Schwameder H, Pigozzi F, Massazza G (2009) Take-off analysis of the Olympic ski jumping competition (HS-106 m). *J Biomech* 42(8):1095–1101. <https://doi.org/10.1016/j.jbiomech.2009.02.026>
16. Li X, Wang X, Chen L, Zhao T (2023) Effects of body angles on the aerodynamic characteristics in the flight period of ski jumping: A simulation study. *Sports Biomech* 24(5):1385–1399. <https://doi.org/10.1080/14763141.2023.2269556>
17. Jølstad PAH, Gilgien M, Elfmark O (2023) Investigation of individual strategies in the aerial phase in ski jumping. *Sci Rep* 13(1):22505. <https://doi.org/10.1038/s41598-023-49683-0>
18. Jansson N, Bale R, Onishi K, Tsubokura M (2019) CUBE: A scalable framework for large-scale industrial simulations. *Int J High-Performance Comput Appl* 33(4):678–698. <https://doi.org/10.1177/1094342018816377>
19. Boris JP, Grinstein FF, Oran ES, Kolbe RL (1992) New insights into large eddy simulation. *Fluid Dyn Res* 10(4–6):199–228
20. Grinstein FF, Margolin LG, Rider WJ (eds) (2007) *Implicit Large Eddy Simulation: Computing Turbulent Fluid Dynamics*. Cambridge University Press
21. Nakahashi K (2003) Building-cube method for flow problems with broadband characteristic length. In: Armfield S, Morgan P, Srinivas K (eds) *Computational Fluid Dynamics* 77–81. Springer, Berlin Heidelberg
22. Bale R, Patankar NA, Jansson N, Onishi K, Tsubokura M (2020) Stencil Penalty approach based constraint immersed boundary method. *Comput Fluids* 200:104457

23. Bhalla APS, Bale R, Griffith BE, Patankar NA (2013) A unified mathematical framework and an adaptive numerical method for fluid-structure interaction with rigid, deforming, and elastic bodies. *J Comput Phys* 250:446–476
24. Yamamoto K, Tsubokura M, Ikeda J, Onishi K, Baleriola S (2016) Effect of posture on the aerodynamic characteristics during take-off in ski jumping. *J Biomech* 49(15):3688–3696. <https://doi.org/10.1016/j.jbiomech.2016.09.037>
25. Cao L, Guo Y, Li X, Chen L, Wang X, Zhao T (2022) Optimization of Ski Attitude for the In-Flight Aerodynamic Performance of Ski Jumping. *Biology* 11(9):1362. <https://doi.org/10.3390/biology11091362>
26. Lee K, Park M, Kim K (2012) Optimization of ski jumper's posture considering lift-to-drag ratio and stability. *J Biomech* 45(12):2125–2132. <https://doi.org/10.1016/j.jbiomech.2012.05.036>
27. Ryu M, Cho L, Cho J (2015) Aerodynamic analysis of postures of ski jumpers during flight using computational fluid dynamics. *Trans Japan Soc Aeronaut Space Sci* 58(4):204–212. <https://doi.org/10.2322/tjsass.58.204>
28. Zhang L, Li X, Wang X, Chen L, Zhao T (2022) Performance and Biomechanics in the Flight Period of Ski Jumping: Influence of Ski Attitude. *Biology* 11(5):671. <https://doi.org/10.3390/biology11050671>

Figures

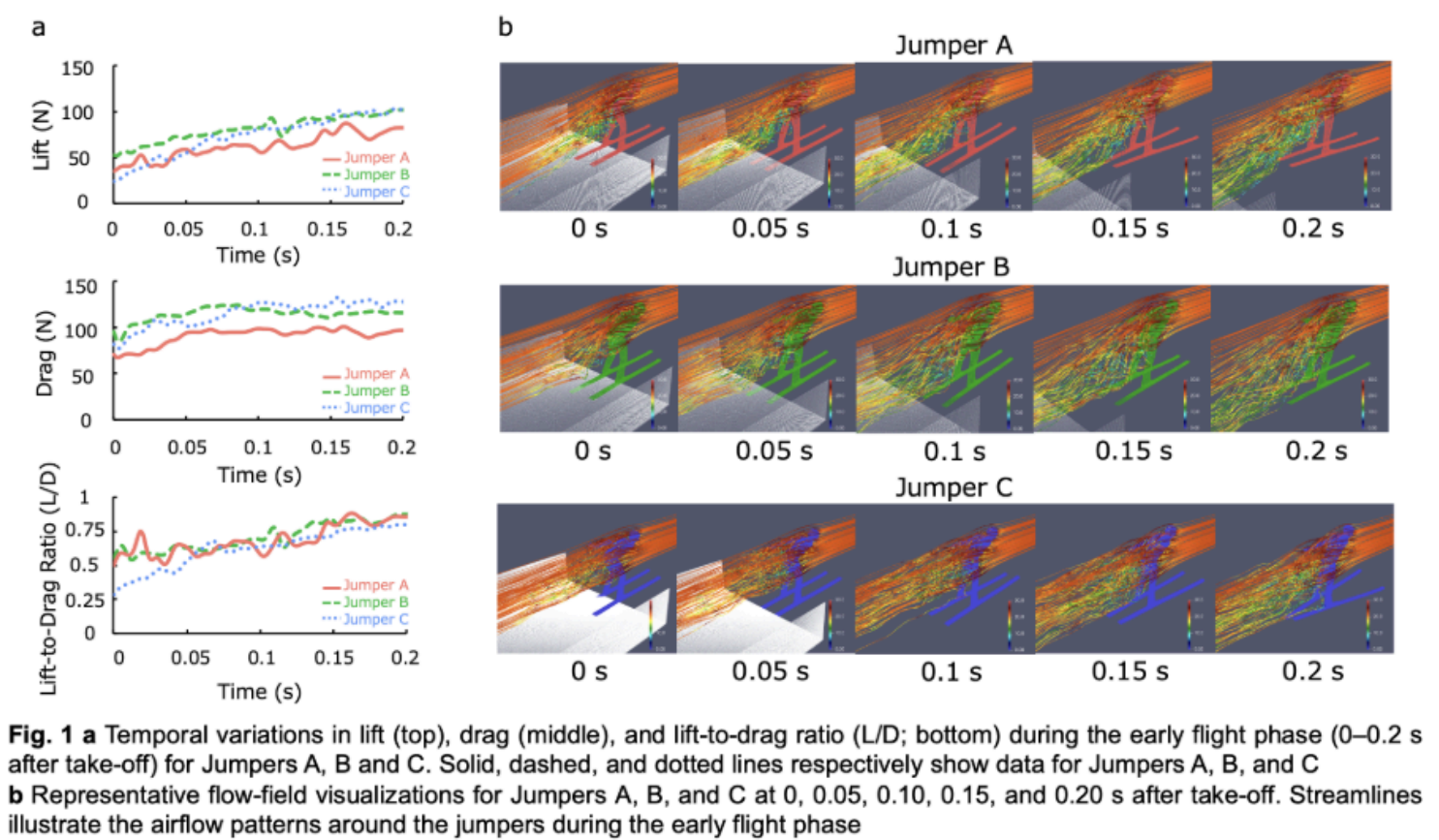


Figure 1

See image above for figure legend

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInfomation.docx](#)