AERODYNAMIC ANALYSIS OF SKIING POSITIONS

INTRODUCTION

In alpine ski racing, **speed is everything — and speed comes down to physics**. Among the forces acting on a skier, aerodynamic drag is one of the most significant, especially at high velocities. The way a skier positions their body while descending can dramatically influence their speed, energy efficiency, and overall race performance.

Figure 1. The author, Alessandro Cantele, racing at the 2025 Junior World Ski Championships in Tarvisio, Italy. Though captured mid-run in a far-from-perfect tuck, this real-world moment helped inspire the aerodynamic investigation at the core of this project.

This project set out to explore the aerodynamic impact of different skiing positions, focusing specifically on the contrast between an upright stance and a deep racing tuck. Through simulation, 3D modeling, and fluid dynamics analysis, the goal was to determine how different positions affect drag.

As a competitive skier myself, this study provided a unique opportunity to combine personal experience on the mountain with scientific analysis — to quantify what athletes feel intuitively: form equals speed.

METHODOLOGY

This study involved a comparison of **aerodynamic drag** between two alpine skiing positions: a racing tuck and an upright stance. The aim was to calculate and compare the drag forces acting on each position, and to evaluate how these forces influence skier speed. The analysis was carried out using established aerodynamic equations and 3D body models designed to reflect realistic skier dimensions.

High-fidelity 3D models of two skiing postures—a full racing tuck and an upright standing position—were captured using the Polycam LiDAR scanning application on an iPhone. A single subject was scanned in both poses to maintain consistency in body proportions and minimize variability.

The resulting 3D meshes were imported into Autodesk Meshmixer for post-processing. This included cleaning up non-manifold edges, smoothing surface artifacts, and preparing watertight models suitable for simulation.

To quantify effective frontal area, the cleaned models were brought into Blender, where orthographic projections were used to measure the surface

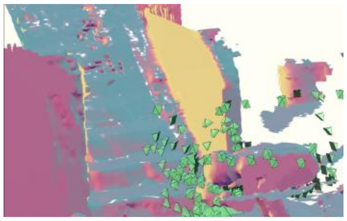

Figure 2. Visualization of the 3D scanning process using the Polycam app. The green triangles indicate the camera path and angle coverage during the LiDAR scan, capturing the subject in a full tuck position for later aerodynamic analysis.

area directly exposed to oncoming airflow. These measurements were later incorporated into drag force calculations.

Both final posture models were then imported into Autodesk CFD 2024, where simulations were performed in a controlled environment with a uniform 25 m/s airflow. Drag force values were extracted from these simulations for further aerodynamic analysis.

This aerodynamic analysis was based on fundamental fluid dynamics and mechanical physics principles, applied using computational tools and 3D modeling techniques. The fundamental methodology of the project can be broken down into the following three main mathematical stages.

Figure 3.Raw 3D scan output of the tuck position captured using Polycam. This unprocessed mesh served as the starting point for model cleanup and aerodynamic simulation workflows.

While this analysis focused on aerodynamic drag, kinetic friction between skis and snow is another factor influencing real-world ski velocity.

Research measuring 114 alpine ski runs reported a mean coefficient of kinetic friction of:

$$\mu_k = 0.054 \pm 0.018$$

with values ranging from 0.023 to 0.139 depending on surface preparation, snow texture, and temperature [1].

These findings indicate that competitive race setups can reduce ski-snow friction substantially. Overestimating this value in simulations could lead to underprediction of realistic race velocities.

1) MODELING DRAG FORCE

The core equation used to analyze aerodynamic drag was the steady-state drag force formula:

$$F_D = \frac{1}{2} \cdot \rho \cdot v^2 \cdot C_D \cdot A$$

Figure 4. Silhouette of skier in the standing position used to calculate effective frontal area. This projection was analyzed in Blender to determine the surface area exposed to airflow

Where:
ρ = 1.20473 kg/m³ (air density, standard atmospheric conditions)
v = 25.0 m/s (relative velocity of airflow)
C_D = experimentally calculated drag coefficient
A = effective frontal area (m²)

2)DERIVING DRAG COEFFICIENTC_D

After running simulations in Autodesk CFD 2024, the drag force F_D , was obtained directly from the software. The **frontal surface area A** was measured from 3D models using Blender.

To isolate and solve for C_D , the drag equation was rearranged algebraically:

$$C_D = \frac{2F_D}{\rho v^2 A}$$

Using this expression, the following was calculated:

- $C_D = 1.79$ for the **standing** position
- $C_D = 0.68$ for the **tuck** position

These coefficients quantified the aerodynamic efficiency of each body posture.

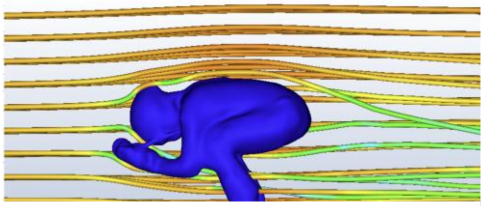

Figure 5. CFD simulation of a skier in the tuck position at 25 m/s airflow. Streamlines visualize airflow behavior, showing minimal separation and a narrow wake region — indicators of reduced drag and optimized aerodynamic posture.

3)CALCULATING TERMINAL VELOCITY

To understand the velocity limits of a skier constrained only by aerodynamic drag, the terminal velocity (V_t) was derived from the balance of gravitational and drag forces:

$$V_t = \sqrt{\frac{2 \cdot m \cdot g}{\rho \cdot C_D \cdot A}}$$

Where:

m = skier mass (constant)

g = gravitational acceleration (9.81 m/s²)

what was analyzed was relative changes in terminal velocity based on differences in C_D and A

EMPIRICAL PARAMETERS AND FORCE COMPUTATIONS

The two position configurations yielded the following key input parameters:

Position	C_D	$A \ (m^2)$	$F_D \ (N)$
Standing	1.79	0.600	404.29
Tuck	0.68	0.314	80.51

As per substitution into the equation:

$$F_D = \frac{1}{2} \cdot \rho \cdot v^2 \cdot C_D \cdot A$$

The drag in the standing position was over 5× greater than that in the tuck position, significantly impacting velocity and energy conservation.

KINEMATIC IMPLICATIONS ON VELOCITY

Free-Fall Terminal Velocity

To establish a theoretical upper bound for skier speed, terminal velocity as if the skier were in vertical free-fall was initially calculated, with air resistance as the only opposing force. At terminal velocity, gravitational force is balanced by aerodynamic drag:

$$mg = \frac{1}{2} \cdot \rho \cdot v^2 \cdot C_D \cdot A$$

$$\Longrightarrow$$

$$v = \sqrt{\frac{2mg}{\rho C_D A}}$$

Where:

- m=68.04kg (mass of skier)
- g=9.81 m/s2g (acceleration due to gravity)
- ρ=1.20473 kg/m3 (air density)
- C_D= drag coefficient
- A = frontal surface area (m²)

Using this model:

Position	C_D	$A\ (m^2)$	**Terminal Velocity (km/h)**
Tuck	0.68	0.314	259.34
Standing	1.79	0.600	115.63

These values represent the maximum possible velocities a skier could theoretically reach during vertical free-fall in air. While informative, this model does not reflect real slope-based skiing, where only a portion of gravitational force acts along the slope surface due to frictions.

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2. Slope-Based Terminal Velocity

To simulate real skiing conditions, velocity was modeled on an inclined slope by balancing the downhill component of gravitational force with drag and friction:

$$mg \cdot \sin(\theta) = \frac{1}{2} \cdot \rho \cdot v^2 \cdot C_D \cdot A$$

$$v = \sqrt{\frac{2mg \cdot \sin(\theta)}{\rho C_D A}}$$

Then terminal velocity for three slope angles — 20°, 30°, and 40° — was calculated to simulate terrain ranging from recreational steepness to elite-level speed skiing gradients.

Slope (°)	**Tuck Velocity (km/h)**	**Standing Velocity (km/h)**
20°	151.67	67.63
30°	183.38	81.77
40°	207.92	92.71

These results show that:

- Tuck posture significantly reduces drag, enabling higher terminal velocities.
- Velocity increases **nonlinearly** with slope steepness.
- Even on a 40° slope — comparable to elite speed skiing courses — the standing position remains under 100 km/h, while a well-executed tuck can theoretically exceed **207 km/h**.

This analysis confirms that **body position and slope gradient are critical factors** in maximizing downhill speed. The difference between aerodynamic and non-aerodynamic form is not just theoretical — it's the difference between racing speeds and recreational descent.

INTERPRETATION

The data clearly demonstrates the profound aerodynamic advantage of a low tuck position over standing upright. In every slope scenario analyzed — from 20° to 40° — the tuck position enabled significantly higher terminal velocities, exceeding 200 km/h under optimal conditions. This difference is driven primarily by the reduced drag coefficient and frontal area in the tucked form, both of which contribute exponentially to increased velocity due to the square root relationship in the governing equations.

To put these findings in perspective, the **fastest speed ever recorded on skis** is **255.5 km/h**, achieved by **Simon Billy** in 2023 at the Vars Speed Masters event in France [2]. However, this record was set under the following optimized conditions:

- On a meticulously prepared, nearly straight **48° gradient**
- With aerodynamic fairings added to the skier's helmet, boots, and back
- Using specially designed speed suits and skis, all intended to **minimize drag beyond what is legal or possible in alpine ski racing**

In contrast, the analysis in this paper is grounded in **traditional alpine racing technique** — with realistic human body posture and no external fairings. The subject modeled is representative of a competitive downhill skier in standard FIS racing gear, skiing in a conventional tuck position.

Even without any aerodynamic enhancements, the model predicts velocities exceeding **207 km/h** on a 40° slope, which is remarkably close to the realm of elite-level speed skiing. This suggests that under the right conditions, **pure body posture alone** can account for the majority of speed gains in real races — long before exotic gear comes into play.

These findings emphasize that aerodynamic form is not just a marginal gain — it is foundational to downhill ski racing performance. Even minor deviations from the ideal tuck can introduce significant drag, leading to measurable losses in speed and race time. For competitive skiers, maintaining aerodynamic discipline is as important as edge control or line choice.

Finally, this study demonstrates the value of merging **computational tools with athletic insight**. Through simulation, measurement, and physics-based modeling, we can quantify what elite skiers already feel on the hill — that **speed is earned through precision, not just courage.**

RESULTS

The aerodynamic simulation revealed a significant difference in drag force and resulting velocity between the upright standing posture and the aerodynamic tuck. Using a modeled skier mass of 68.04 kg and a constant airflow speed of 25 m/s, drag force data extracted from CFD simulations showed that the tuck position produced a drag force of only 80.51 N, compared to 404.29 N in the standing posture. The corresponding frontal areas were 0.314 m^2 for the tuck and 0.600 m^2 for the standing position. These differences resulted in drag coefficients of 0.68 and 1.79, respectively.

These aerodynamic values were then used to calculate terminal velocities in both vertical free-fall and slope-based scenarios. In vertical free-fall, the skier in a tuck could theoretically reach 259.34 km/h, while the standing posture would only allow for a maximum of 115.63 km/h. When factoring in slope inclination, the effect of posture remained just as significant. On a 20-degree slope, the tuck reached 151.67 km/h, while standing reached just 67.63 km/h. At a 30-degree slope, those values increased to 183.38 km/h and 81.77 km/h, respectively. On a 40-degree gradient — representative of elite racing conditions — the tuck position achieved 207.92 km/h, while the standing posture still remained below 100 km/h, topping out at 92.71 km/h.

These results confirm that aerodynamic posture plays a dominant role in determining downhill speed. The fact that, under identical environmental conditions and mass, the skier in a tuck can reach speeds over 115 km/h faster than when standing highlights the exponential effect of drag. In high-speed alpine racing, posture isn't just important — it's decisive.

CONCLUSION

This aerodynamic analysis underscores the critical role that posture plays in determining speed and performance in alpine skiing. Through computational modeling, it became clear that the tuck position dramatically reduces drag and enables significantly higher terminal velocities compared to an upright stance—often by more than 100 km/h under identical slope and environmental conditions.

While elite speed skiing records involve additional optimizations like fairings and steeper terrain, this study shows that even without such enhancements, traditional racing posture alone accounts for the majority of aerodynamic gains. On a 40-degree slope, a well-executed tuck can propel a skier to speeds exceeding 200 km/h, rivaling specialized speed events.

Ultimately, the findings affirm what competitive skiers intuitively understand: **technique and form are just as vital as strength and equipment**. In a sport where milliseconds matter, maintaining an aerodynamic posture isn't just about looking fast—it's about being fast. This study bridges the gap between physics and performance, offering quantifiable evidence that aerodynamics is not a marginal detail, but a cornerstone of speed in alpine racing.

ATTRIBUTION

All 3D scans, aerodynamic simulations, data collection, and analytical calculations in this project were conducted by the author. The 3D models were captured using the Polycam LiDAR scanning application on an iPhone, cleaned in Autodesk Meshmixer, and measured in Blender. Simulations were performed using Autodesk CFD 2024, and all drag force outputs were used to calculate velocity profiles manually by the author.

Textual content, formatting, and structural editing of the final written report were refined with the assistance of **ChatGPT (OpenAI)**. This support was limited to phrasing, tone adjustments, and clarity improvements—no core content, analysis, or conclusions were generated by AI. A complete version of the original, unedited draft is retained by the author to demonstrate full authorship and academic integrity.

As workflows across engineering, research, and industry evolve, so too must the academic process. The responsible use of AI tools like ChatGPT reflects how professionals now write, iterate, and communicate complex ideas efficiently. This project embraces that shift while maintaining full transparency and authorship.

Special thanks to Ashley Anderson for being the 3D scan model used in this project—and for holding a perfect racing tuck for an *unreasonably* long time while being scanned. This project would not have been possible without her patience, support, and posture.

Figure 6. Ashley Anderson, the dedicated scan model, collapsed in full ski gear after holding a tuck through multiple failed 3D scans. The pose had to be repeated half a dozen times due to scan errors—true aerodynamic commitment.

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