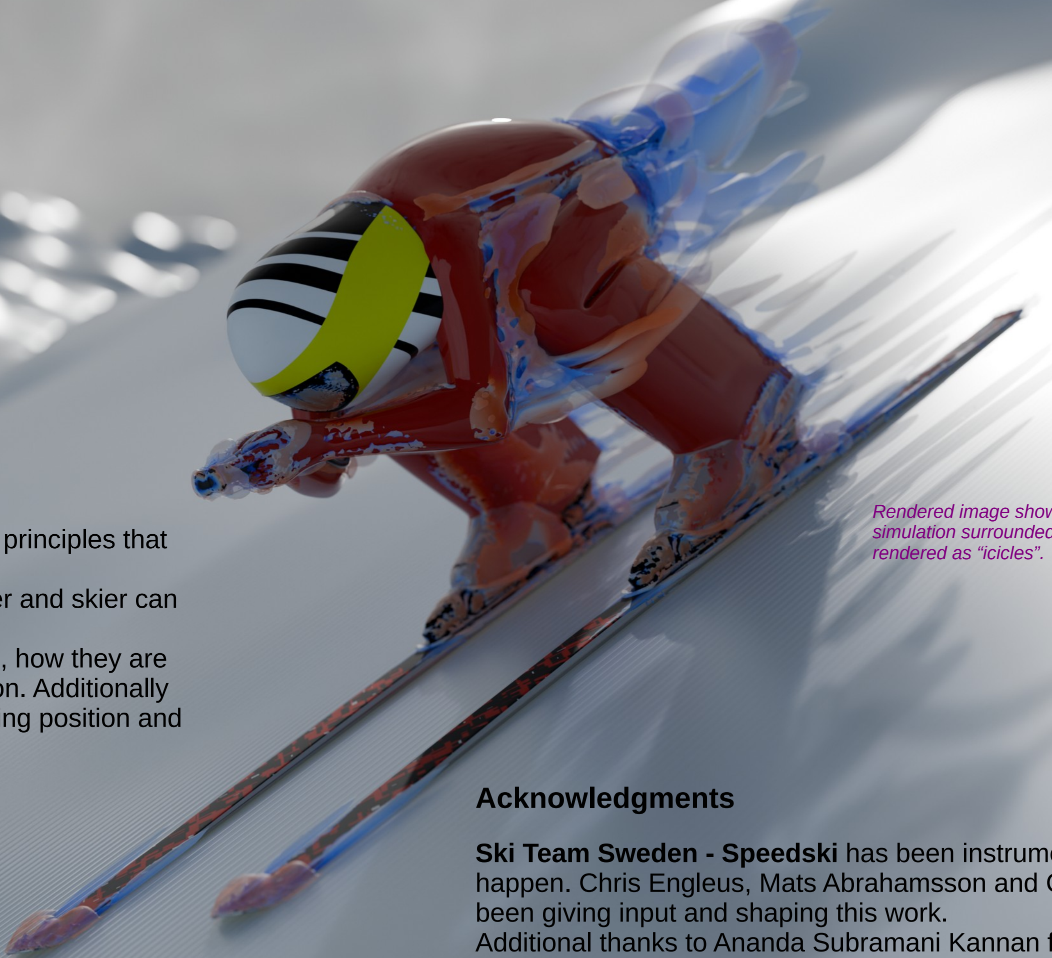
FUNDAMENTALS OF

Speed Ski Aerodynamics

by Vojtech Sedlak

Abstract

Using CFD tools to understand the basic aerodynamic principles that affect a skier in the particular discipline “Speed Ski”.
It is a discipline where top speed determines the winner and skier can use some aids to further improve their aerodynamics.
Focus is on understanding the magnitude of the forces, how they are connected to wind tunnel tests and a real world situation. Additionally some investigations of basic positions and how the skiing position and equipment can be be improved.



Rendered image showing the skier from CFD simulation surrounded by Q-crit contour surface rendered as “icicles”.

SKI TEAM SWEDEN SPEEDSKI

SVENSKA SPEL

VOLVO

Acknowledgments

Ski Team Sweden - Speedski has been instrumental in making this happen. Chris Engleus, Mats Abrahamsson and Carl Ribbegårdh have been giving input and shaping this work.
Additional thanks to Ananda Subramani Kannan for his thoughts on the CFD procedure.
Final thanks to Volvo Cars for Windtunnel testing opportunities and Svenska Spel for sponsorship.

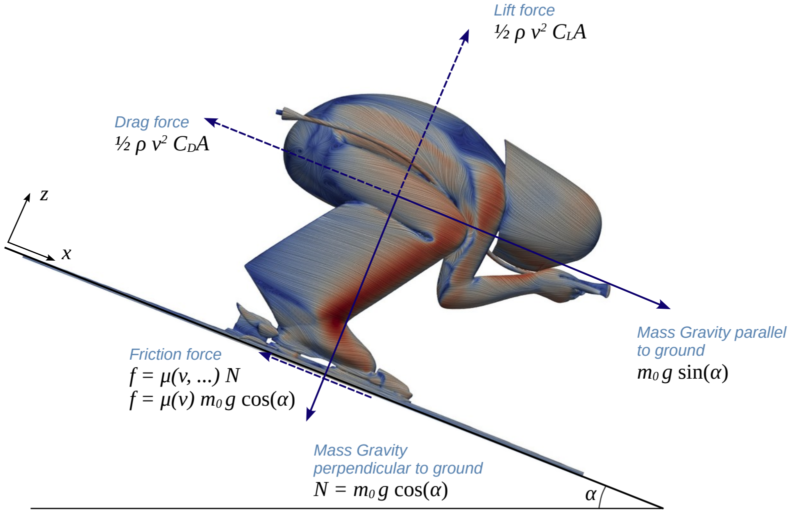
Nomenclature

ρ_∞	Density of air in freestream *[kg/m³]*
A	Refence area *[m, m²]*
C_D	Coefficient of Drag *[-]*
C_L	Coefficient of Lift *[-]*
C_DA, CdA	Coefficient of Drag * reference Area *[m²]*
C_LA, ClA	Coefficient of Lift * reference Area *[m²]*
F_n	Force in *n* direction *[N]*
f	Friction Force *[N]*
g	Gravity *[m/s^2]*
μ	Friction Coefficient *[-]*
m_0	Mass of skier *[kg]*
N	Normal Force *[N]*
v_∞	Velocity in freestream *[km/h]*
CFD	Computanional Fluid Dynamics
CpTot	Pressure coefficient of total pressure: $Cp + 1/2\rho_\infty v_{mag}^2$
LE	Leading Edge
TE	Trailing Edge
LIC	Line Integral Convolution

Content

Introduction

Forces Acting on a Speed Skier



Acting Forces

There are several forces acting on a speed skier going down a straight slope trying to reach top speed.

- Gravity and mass, depending on the slope angle, are moving the skier forward.
- Two forces are slowing the skier down. Friction against the snow and *aerodynamic drag*.
- Lift force is balanced out by the mass and gravity acceleration acting in the normal direction of the slope.

Aerodynamic drag and *lift* will be the main focus of this document.

Solution is Dynamic not Static

Many scientific papers make the assumption that the problem is static and try to find a “static equilibrium”, which is a very misleading simplification when looking at total aerodynamic contributions.
To better understand the impact of aerodynamics on a skier, it has to be seen as a dynamic problem, since the skier is constantly accelerating and even decelerating due to shifting slope angle.
Accelerating as much as possible, in the beginning where the slope is steep and trying to maintain as much of it when reaching the flat finish-line.

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} v \\ \frac{1}{m_0}\left(m_0\, g \sin(\alpha) - \mu(v)\, m_0\, g \cos(\alpha) - \frac{1}{2} \rho\, v^2 C_D\, A \right) \end{bmatrix}$$

Values to solve
The value x is the distance. Time derivative ẋ (or x’) is velocity v and second time derivative is acceleration. x” = v’ = a

Mass Gravity parallel to ground
$m_0\, g \sin(\alpha)$

Friction forces
$\mu(v)\, m_0\, g \cos(\alpha)$

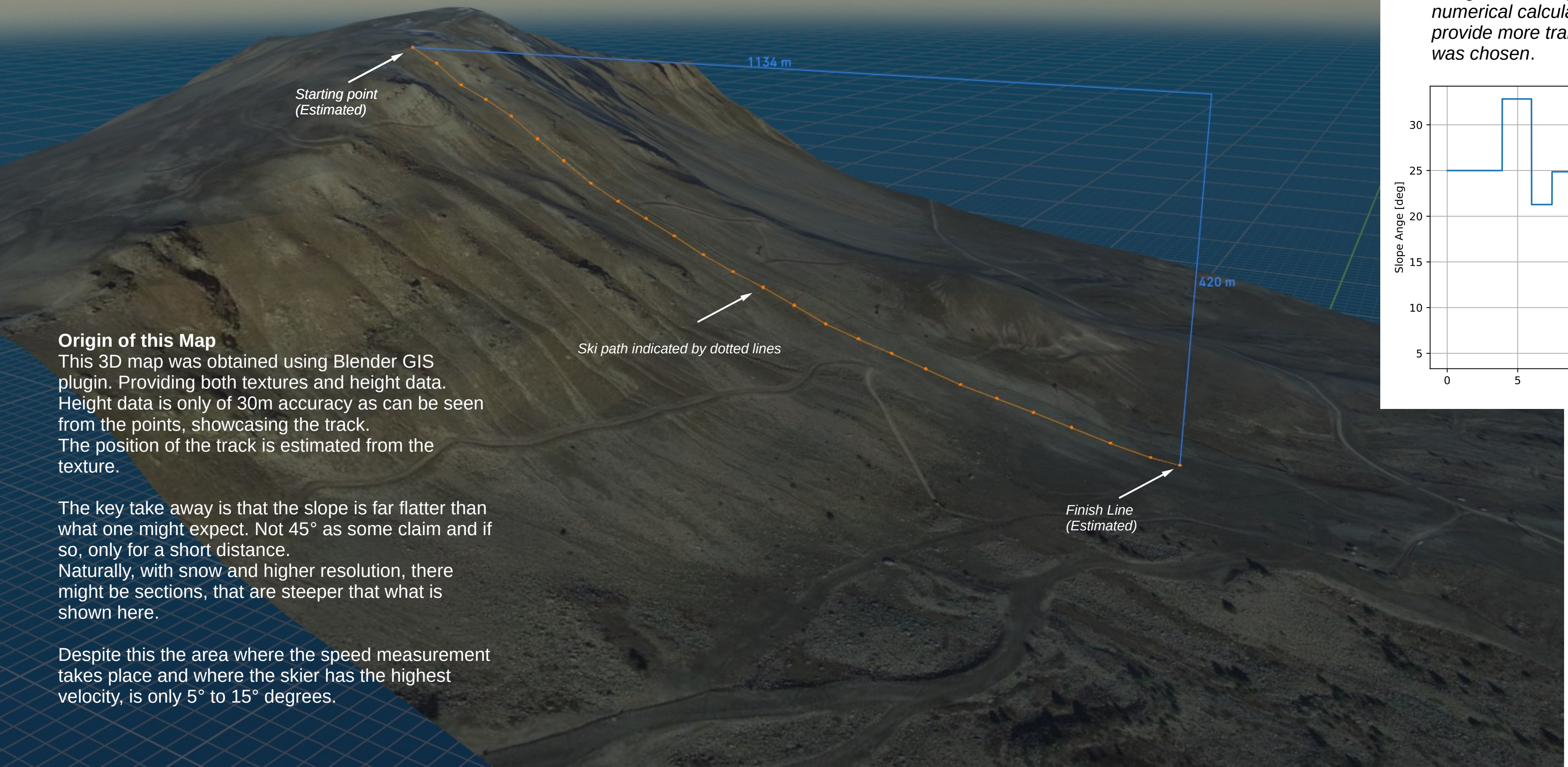
Drag forces
$\frac{1}{2} \rho\, v^2 C_D A$

Solving a Differential equation

Since the problem is dynamic and non-linear it is easier to solve it numerically. Thus, properties of the ski slope and the skier needs to be established.

Properties of a Ski slope – Vars (France)

To better understand the properties of speed skiing it is essential to investigate an actual slope where records are broken. Even thou it is challenging to get it accurate, it will show in what magnitude certain variables are, how they interact and what range of forces, thus CdA values to expect.

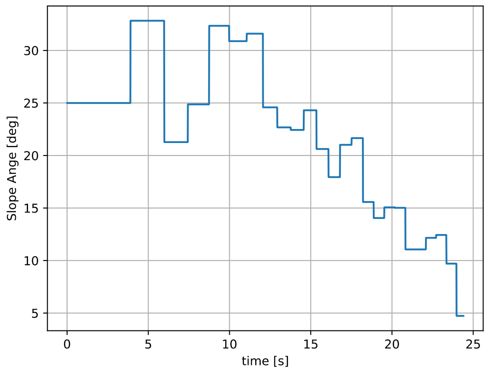


Origin of this Map
This 3D map was obtained using Blender GIS plugin. Providing both textures and height data. Height data is only of 30m accuracy as can be seen from the points, showcasing the track.
The position of the track is estimated from the texture.

The key take away is that the slope is far flatter than what one might expect. Not 45° as some claim and if so, only for a short distance.
Naturally, with snow and higher resolution, there might be sections, that are steeper that what is shown here.

Despite this the area where the speed measurement takes place and where the skier has the highest velocity, is only 5° to 15° degrees.

Slope Angle Changing over Time
The skier will experience 20° to 35° degrees in the first ~15 sec of the track. Then steadily flattening out.
In the figure below, it is represented with discrete steps. It can also be smoothen out using curve fitting which makes the numerical calculations easier. However, to provide more transparency, discrete method was chosen.



Solving Forces

With the knowledge of the race track and forces acting on the skier, next step is to add variables and solve the differential equation with ODE solver, such as SciPy, and see the results.

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} v \\ \frac{1}{m_0}\left(m_0 g \sin(\alpha) - \mu(v)\, m_0 g \cos(\alpha) - \frac{1}{2}\rho v^2 C_D A \right) \end{bmatrix}$$

Values to solve
$x'' = v' = a$

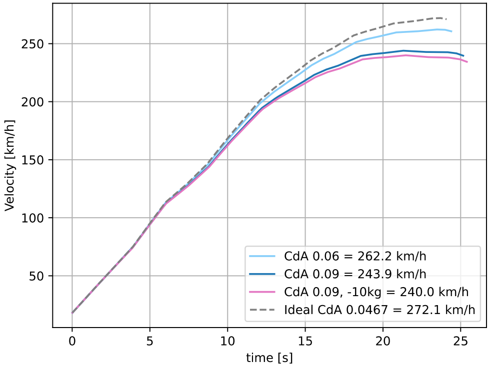
f0
Zero order. Gravity acceleration dependent on ski slope angle. This is what moves skier forward.

f1
First order. Surface friction increases with velocity and reduces with ski slope angle. Note that this is a very crude way of expressing the complexity of snow and ski interaction at low and high velocity.

f2
Second order. The aerodynamic part with increases by velocity squared.

Assumed Values

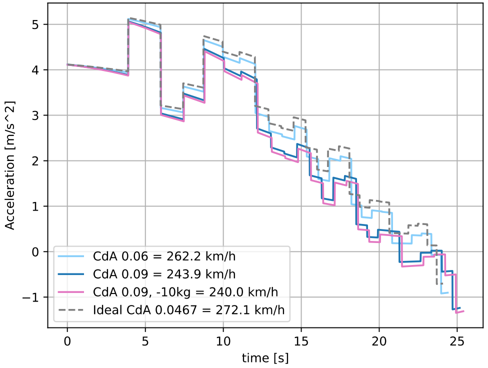
m_0	117 [kg]	= skier mass 90 kg + skies 15 kg + skiboots 2*3 kg + helmet 2 kg + poles 2*1 kg + fairings 2*1 kg (skier at 90 kg with all equipment on max weight limit)
g	9.81 [m/s^{-2}]	
ρ	1.01 [kg/m^3], estimated density at 2000m altitude and +2°C	
$\mu(v)$	0.0005 v [-], pure guess to get realistic results.	
$C_D A$	0.06...0.09 [m^2]	This seems to be a realistic span between a good and a worse skier based on CFD results. With a frontal area of 0.3 m^2 the skier has a Cd between 0.20 and 0.27



Velocity profile and Top Speed

Top speed is reached at the end of the track, sometimes even before. As the track flattens out good glide and low aerodynamic drag becomes important.

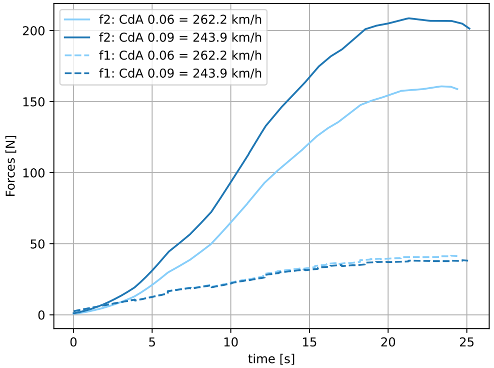
Rule of thumb from these cases:
-0.010 dCdA (10 counts) will give ~**+7 km/h**
-10 kg will give ~**-4 km/h**

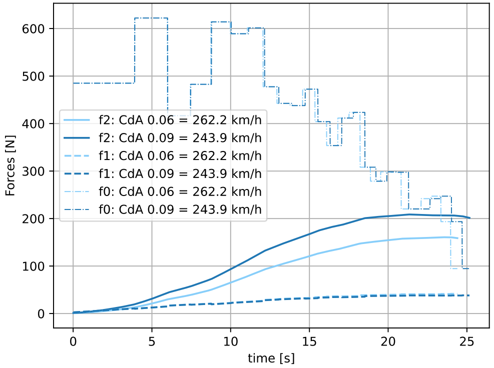


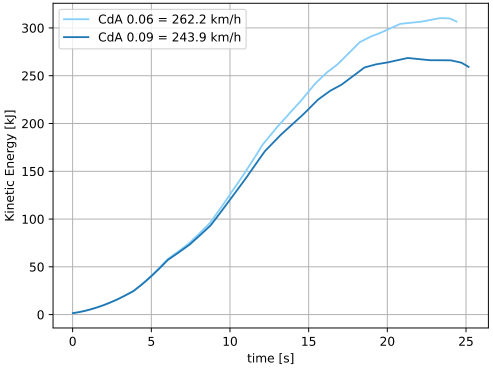
Acceleration over time

Since the underlying ski slope data is discrete there are jumps in acceleration as the slope inclination changes.
Despite this it can be clearly seen that most important part of getting up to speed is in the first part of the track.

Comparing Force-Components







Force contribution of Ground Surface Friction (f1) and Aerodynamic Drag (f2)

This is highly speculative since the behavior of friction is not fully modeled. It is safe to assume however that friction starts off as a higher contributor and is passed, at some velocity, by the drag contribution. More can be done to understand when and how.
Here the friction also increases as the slope angle decreases.

Note the much higher drag force experienced by the slower skier with higher CdA value.

… And Driving Force (f0)

Introducing the driving force puts things more into perspective.
In the steep part of the slope, the skiier is pushing with over 600N to accelerate, building up speed and kinetic energy. The drag and friction forces are just picking up.

At the end of the slope this system starts to reach some sort of equilibrium, where *f0 ≈ f1 + f2*.

Kinetic Energy

The skier with the lower CdA has picked up more kinetic energy which becomes evident closer to finish line.
Since both their masses are the same, the only difference is their respective velocities.

Procedure

Procedure

CFD Workflow

A fully **Free and Open-Source workflow** has enabled a very good integration between each part thanks to modifications and scripting.

Huge Thanks to all those behind these projects! Without these great applications this work would not have been possible!

Iterate

Photos
Pictures of skier taken from various angles

Meshroom

3D Scanning
Create 3D models and reference pictures using photogrammetry

blender

Refine Geometry
Retopology, create armature and modifications

OpenFOAM

Meshing and Simulation
SnappyHexMesh for meshing and FOAM solvers for calculation

ParaView

Post processing
For visualization of results and assets to feed back into Blender

manjaro

All running on Manjaro Linux Distribution which is a variant of Arch Linux.
Other applications that have been essential, but outside the core workflow are Krita, wxMaxima, Inkscape and LibreOffice

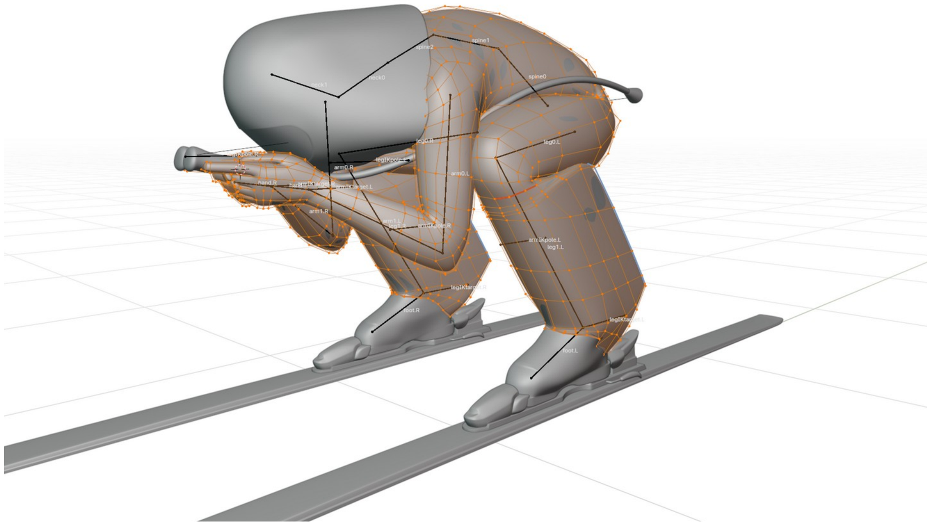
3D Scanning of Skier

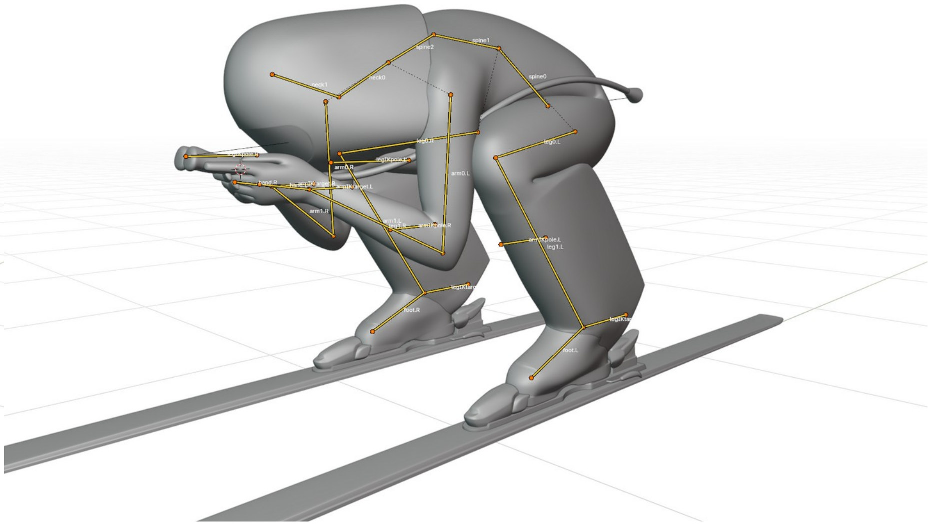
From Photos -> Meshroom -> Blender

To create the skier as accurate as possible with available tools was to take as many pictures of the skier in position as possible.
The difficulty for the person posing, is of course to maintain absolutely still for a longer period, while having breathing restricted by the full-face helmet. Additionally it is challenging to capture obscured areas, which are still very important for aero simulations.

To capture any deviations from what the 3D scanning represented poorly, Meshroom can export positions from where it thinks the photo was taken, and undistort the photo. With a bit of scripting this can be represented in Blender and used for tracing.
Full model can then be rebuilt in Blender.

Procedure
Geometrical Setup





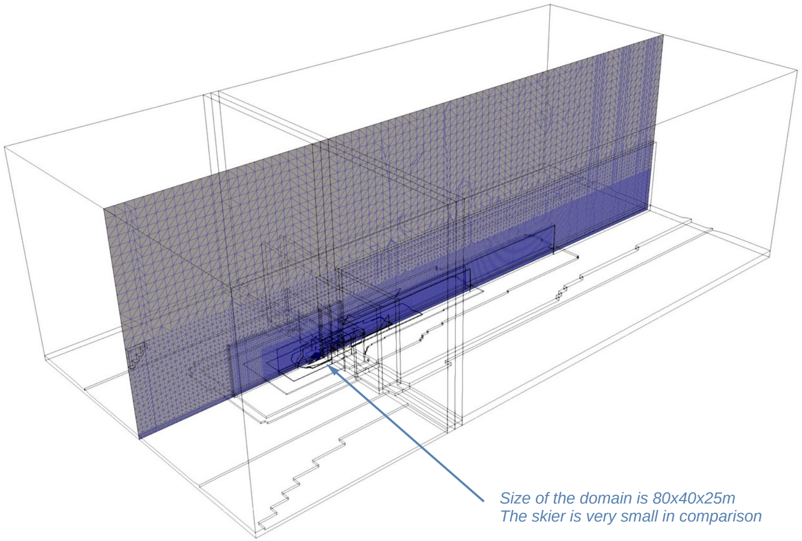
Subdivision Surface

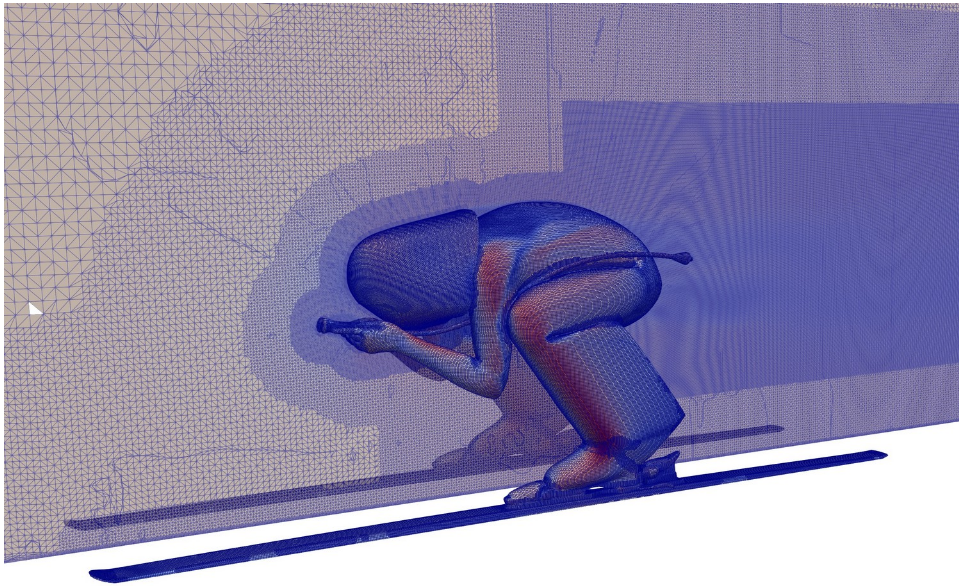
To simplify future modifications, the model is rebuilt into a quad mesh and subdivision modifier is added.
The subdivision is crucial to keep high surface quality for aero-simulations, while making it easy to quickly modify certain areas.
Other modifier as such as e.g. bevel and mirror modifiers are also recommended.

Armature and modifications

Learning from how animated movies are made, it becomes clear that armatures, inverse-kinematics and shape-keys are perfect for easy modification of a skiers position. They can then be archived into an asset library and reused with other configurations.

CFD Meshing and Simulation



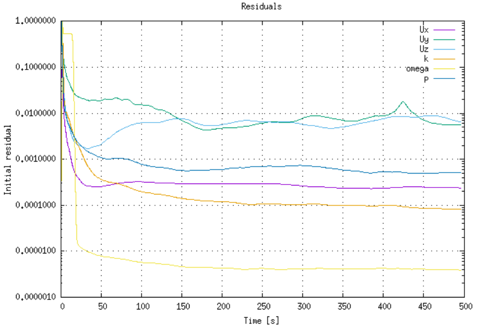


Meshing

Before the flow around the skier can be solved, the surrounding air-volume has to be discretized, i.e. meshed.

Refinement increases as mesh gets closer to the skier and the highest level is 9 (~2mm). Refinements are also added behind the skier to improve the resolution of the wake. This has been noticed to give a very significant impact on the result.
To makes sure that the boundary layer close to a surface is properly resolved, prism/inflation layers are used.

In total there are 100 million cells in the domain.



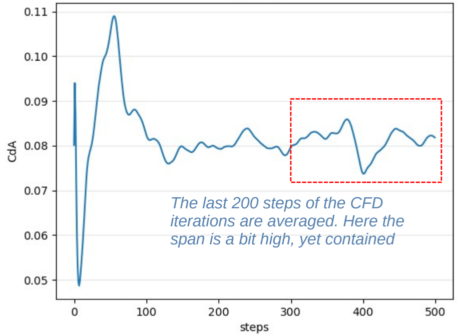
Simulation

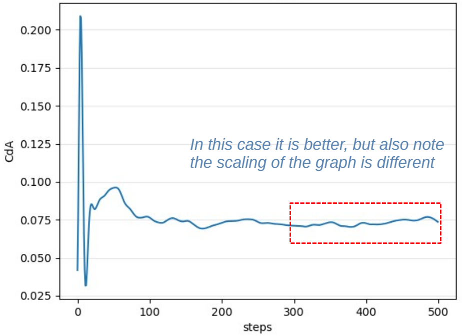
The actual simulation is done using SIMPLE foam solver and using the RANS model kOmegaSST. Results converge typically within less than 500 steps (see figure).
This takes ~8 hours on available AMD Threadripper workstation.

Naturally, full transient models would be preferred over RANS, such as various DDES models, due to huge rear-end separation of the skier. Problem is of course that this would make each simulation about 10 to 20 times more time consuming, which was out of scope at this time.

Interpret CFD Results

When a simulation has finished it is important to understand how to fully interpret the results. This is only a small show case.





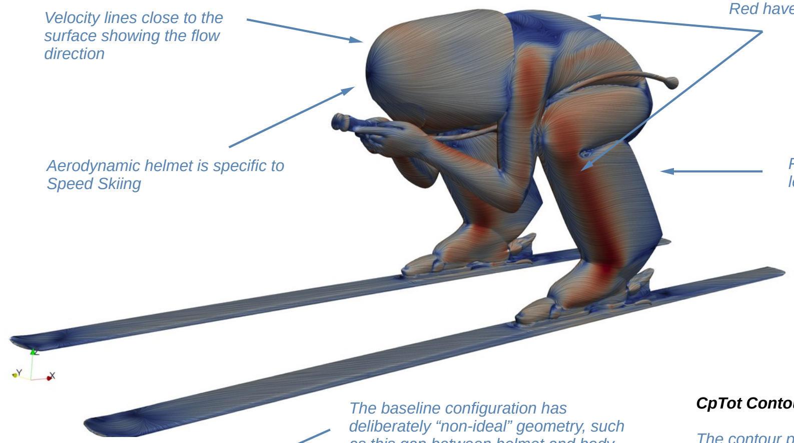
Velocity LIC surface

Velocity lines close to the surface showing the flow direction

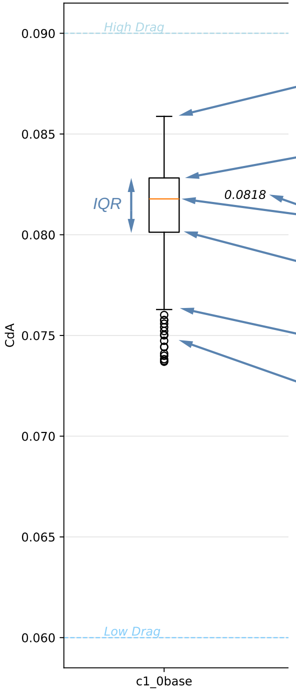
Blue areas have low velocity, Red have high

Aerodynamic helmet is specific to Speed Skiing

Fairings are the airfoil features on the legs, specific to Speed Skiing



Some configurations converge better than others. Thus it is important to also show the quality of results when comparing, not just the numbers. Smaller "box", better quality.



"Maximum" = Q3 + 1.5 IQR

***Q3:** 75th Percentile (Inter Quartile range)*

Median

***Q1:** 25th Percentile*

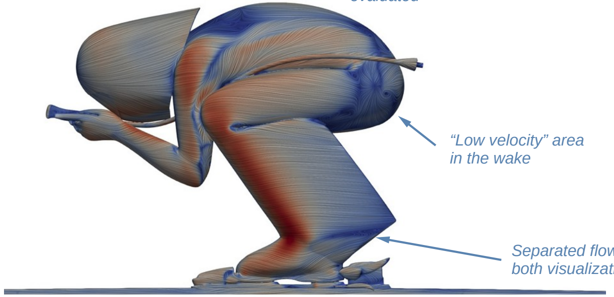
"Minimum" = Q1 – 1.5 IQR

Outliers

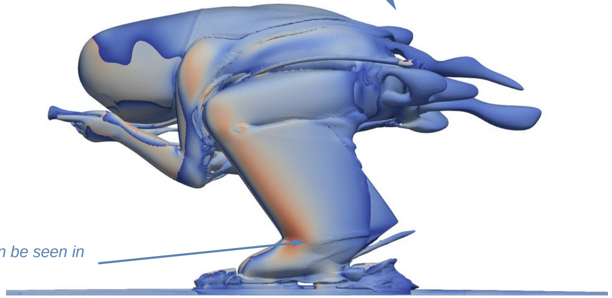
The baseline configuration has deliberately "non-ideal" geometry, such as this gap between helmet and body. That way "improvements" can be evaluated

CpTot Contour plot

The contour plot shows separation volumes to indicate which are potential problem areas



"Low velocity" area in the wake



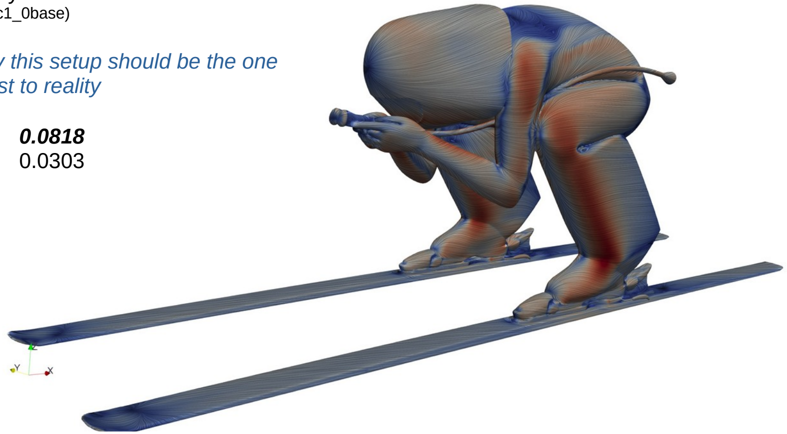
Separated flow can be seen in both visualizations

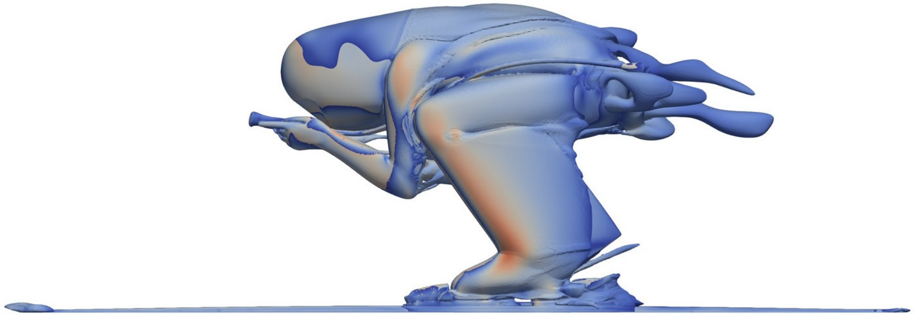
Comparing CFD Domains: “Open slope” – “CFD Wind tunnel rig”

“Open Slope”
This domain-type tries to replicate the full characteristics of a skier moving down a perfectly smooth ski-slope at constant velocity.
(case: c1_0base)

Idealy this setup should be the one closest to reality

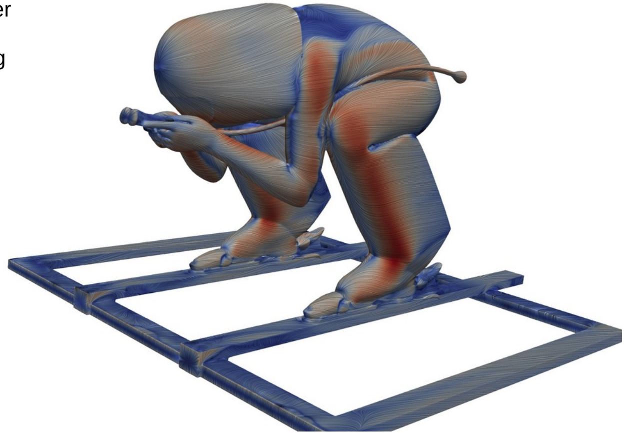
C_DA ***0.0818***
C_LA 0.0303

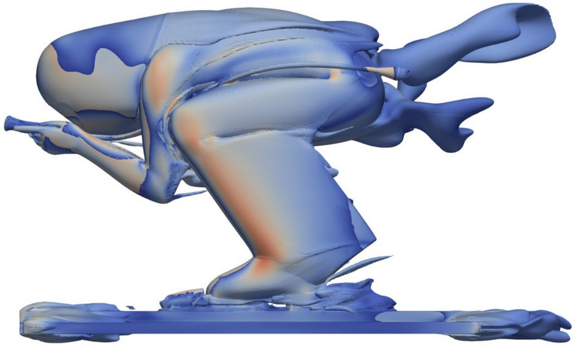




Wind tunnel rig
Since a lot of testing is also performed in a wind tunnel, it is interesting to see the effects of a square-profile rig for the skier to stand on, instead of skies.
This has a great impact on the total drag number, but overall surface flow is fairly similar.
Naturally the wake behind the skier is affected, thus has a different shape and direction.
(case: c1_0base-WTmwg)

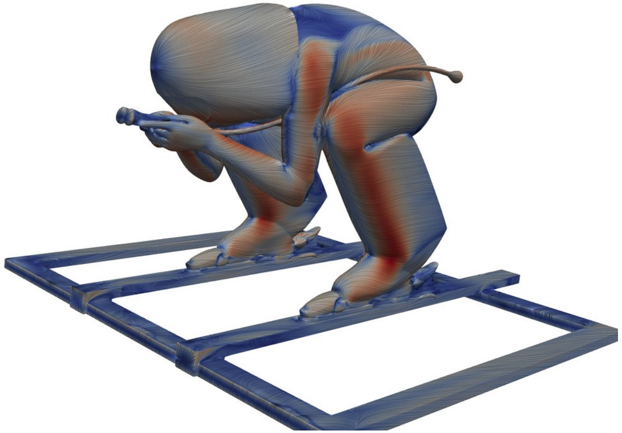
C_DA ***0.1568*** *(+0.075 or +91.7%)*
C_LA 0.0027





Procedure

Comparing “CFD Wind tunnel rig” – Real Wind tunnel Test



From CFD simulation:

Force: $F_x = C_D A \cdot \frac{1}{2} \rho_\infty v_\infty^2 = 257.7$ [N]

$C_D A$: 0.1568 [m²] (case: c1_0base-WTmwg)
ρ_∞: 1.18 [kg/m³]
v_∞: 190 [km/h], 52.8 [m/s]

Conclusion:
The CFD result of the skier on a rig compared to “a wind tunnel measurement” is in this case over-predicting by 11%, which should be considered fairly small, since this type of correlation was never part of the original scope.
The difference can be attributed to the very different skier and rig geometry. Moving ground plane in CFD has the rig floating above ground (compromise for sake of simplicity). The ground in the wind tunel is non-moving with boundary suction and scoop fan in front. The fluid domain size and boundary conditions are naturally also different.

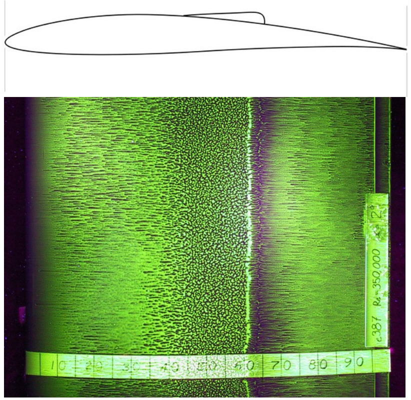
Trying the analysis in reverse and assuming from previous CFD simulation that the fraction between “Open-slope” and “CFD wind tunnel rig” is 0.5217 (1/(1+91.7%)), it would mean that the skier on the picture has a CdA of 0.0737. This would be on the very low-end of the CdA spectrum, which is plausible.[1]

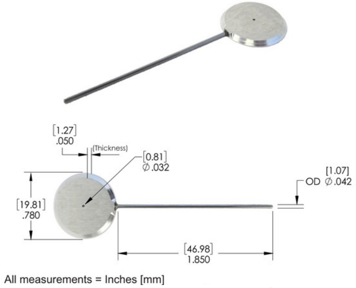
[1] Photo: Swedish Speed Ski Team, Carl Ribbegårdh on picture

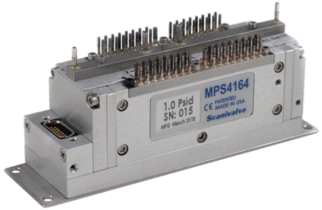
Procedure

Investigating Aerodynamic Flow in Real World

Flow behavior found in CFD should be confirmed in real world, before implementing any radical configurations.
Certain things are actually even easier to fully optimize in the real world, than to do it in CFD. Ideally a good middle step is to test in a wind tunnel, if possible.
Here are examples of methods to better understand flow patterns in the real world.







Tufts

A simple string taped to the surface will show flow separation[1]

Flow Viz

Paint containing colored powder and vaporizing fluid, such as petrol, will show separation, flow direction and perhaps even flow transitions (laminar to turbulent) [2][3]

Surface Pressure Measurement

A “pressure patch” is taped to the surface. A small tubing is connected so that the pressure scanner can read the difference between the “patch” and ambient pressure.

This is one way to do pressure measurement, which is key when correlating CFD with the real world conditions.[4]

[1] NASA Identifier: NIX-EC89-0096-240
[2] https://www.the-race.com/formula-1/gary-andersons-guide-to-flow-vis-in-f1-testing/, (2024)
[3] https://m-selig.ae.illinois.edu/LRNFlowViz.html, (2024)
[4] Scanivalve, scanivalve.com/products (2024)

Results for Fairings

Airfoil Section for Fairings

A popular choice for a fairing section among skiers is typically a traditional NACA profile. Problem is … [REDACTED]

[REDACTED]

Results for Skier

Results for Skier

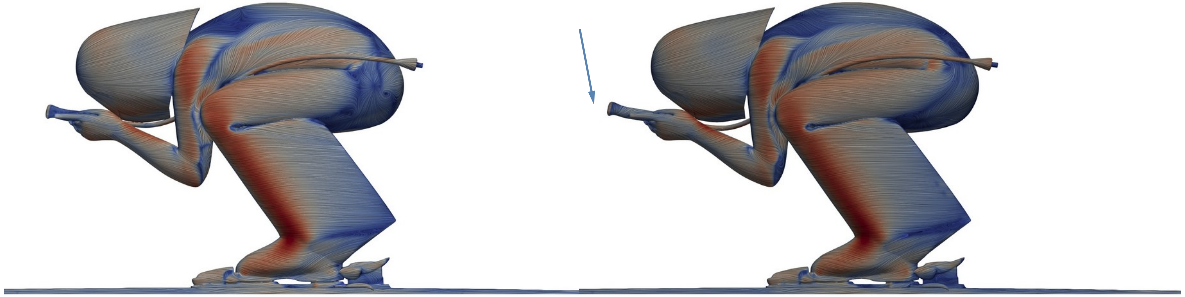
Overview of Investigations

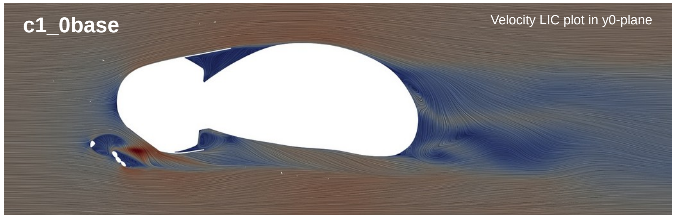
This is a simple overview of C_DA and C_LA for all configurations

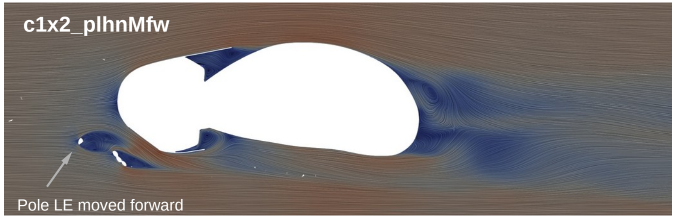
Results

1. Pole-handles moved forward

Pole-handle is positioned further forward in the hands, [REDACTED]

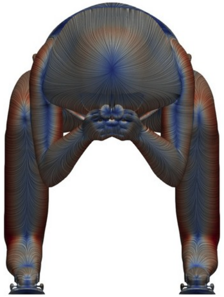






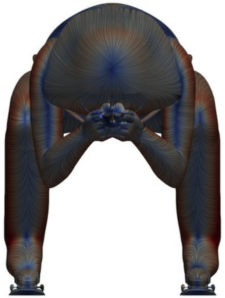
c1_0base
Baseline

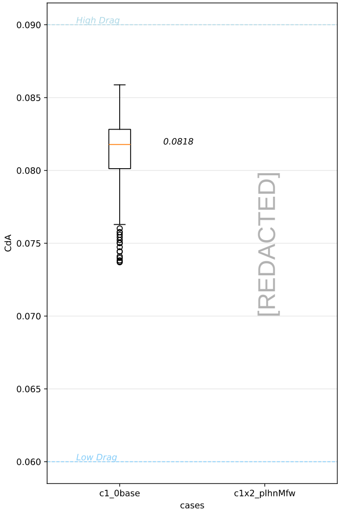
C_DA ***0.0818***
C_LA 0.0303

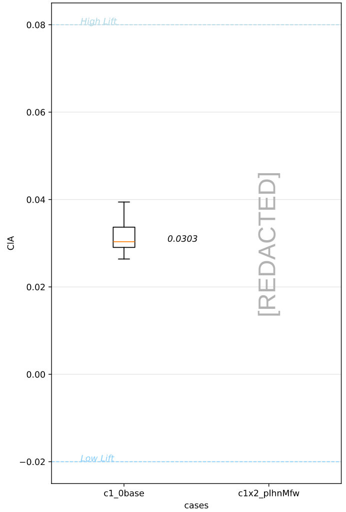


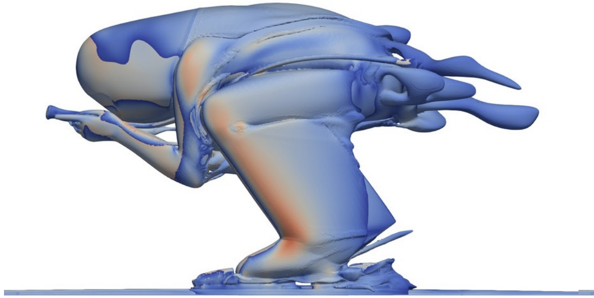
c1x2_plhnMfw
Pole handles mv fw

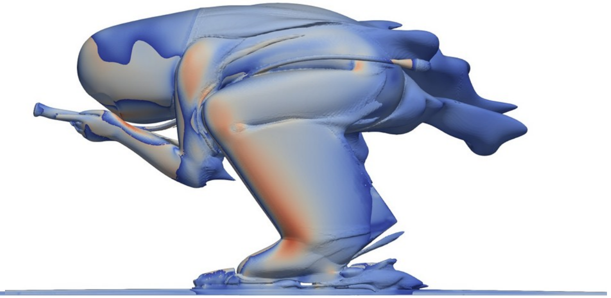
C_DA ***[Redacted]***
C_LA *[Redacted]*



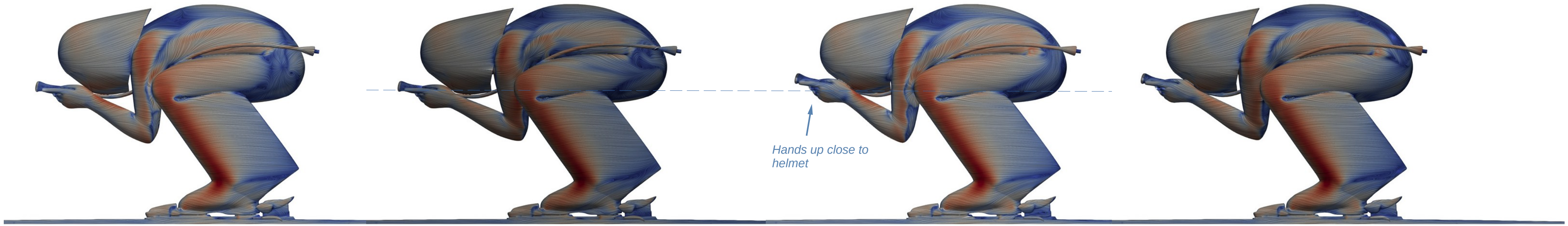






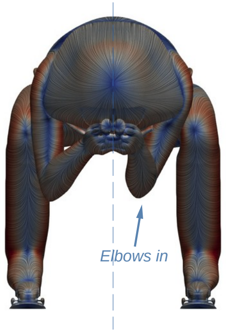


2. Hand Positions



c1_0base
Baseline

C_DA	***0.0818***
C_LA	0.0303

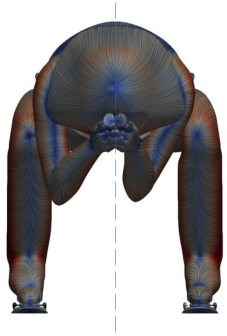


c2_elbowIn
Moving elbows inward

C_DA	***[Redacted]***
C_LA	*[Redacted]*

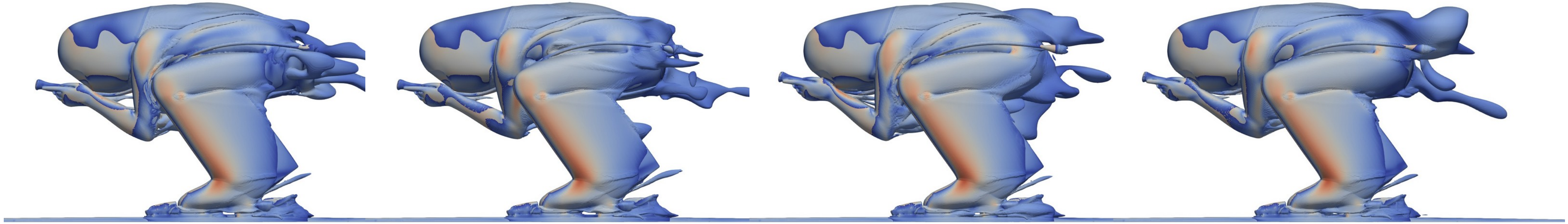
c3_handsUp
Hands upward

C_DA	***[Redacted]***
C_LA	*[Redacted]*



c4_handsUpElbIn
Hands upward + Elbows Inward

C_DA	***[Redacted]***
C_LA	*[Redacted]*



X. [REDACTED]

[REDACTED]

Final Conclusions

It has shown that using CFD to evaluate a Speed-Skiers position and equipment is very useful, [REDACTED]

To be continued...