SWISS SIDE

AERO CALF Sleeves

Research & Development

White Paper

TABLE OF CONTENTS

INTRODUCTION

This white paper summarises a Swiss Side research and development project spanning 18 months, to design uniquely performing, aerodynamically optimized calf sleeves for triathletes. When developed in the right way, calf sleeves can have a significant impact on performance by reducing the aerodynamic drag of the calves (lower legs). In particular, for long-distance races with 180km cycling, time savings measurable in multiple minutes are possible for athletes of all levels.

The aerodynamic drag performance benefit can be achieved by using rough fabrics or special roughness features applied to the fabric, to deliberately induce turbulence to the airflow. However, the actual performance benefit of such calf sleeves can be extremely variable depending on the athlete's leg size and speed. The target of this project was therefore to develop an improved design compared to existing products, which deliver a robust and significant aerodynamic performance benefit for all athletes, regardless of their size, speed, or the wind conditions in which they ride. In order to achieve this, a completely novel, multi-faceted aerodynamics development and testing process was created which is documented in this white paper.

As part of this project, an all-new wind tunnel facility was designed and built at the Swiss Side headquarter in Zürich, Switzerland, with special functionality implemented for textiles R&D and for this particular project.

Figure 1: The final optimised AERO CALF Sleeve solution developed by Swiss Side.
Note that the branded surface is positioned on the back of the leg.

RESEARCH & DEVELOPMENT APPROACH

1. AERODYNAMICS THEORY FOR THE INVESTIGATION OF AERO CALF SLEEVES

Aerodynamic drag is the most significant resistive force a cyclist has to overcome with the exception of when climbing at reasonable gradients. Measures taken to reduce aerodynamic drag will lead to performance improvements.

——

The aerodynamic drag force F_D acting on a body is defined by

$$F_D = 0.5 * \rho * U^2 * Cd * A$$

ρ = air density
U = air speed
Cd = aerodynamic drag coefficient
A = frontal area

——

For many geometries, Cd is effectively a constant and does not change with air speed U or density ρ. In these cases, the aerodynamic drag force F_D increases with the square of air speed and linearly with air density.

——

The rider power P_D to overcome the aerodynamic drag F_D is

$$P_D = F_D * V$$

V = rider ground speed

——

In no wind conditions, air speed U equals ground speed V and rider power P_D increases with the cube of speed. ($P_D \propto V^3$)

Typically, an athlete can reduce their aerodynamic drag force F_D by reducing their frontal area A or by reducing the Cd.

In cycling, frontal area reductions on the athlete are typically achieved by more aggressive riding positions, whereby the shoulders and head are lowered and similarly, more narrow arm position setups are used, all to create a more compact position with minimal frontal area A. However, such positions can negatively impact physiology, reducing the rider power output and also reducing comfort, increasing fatigue.

Focusing on reductions in Cd, these can be achieved with more aerodynamically optimised equipment, for example with a bike frame with aero tube profiles, helmets, deep section wheels etc. However, at the speeds of cycling, for some geometries and in certain conditions, significant changes in Cd do occur through relatively small changes in the air speed with no change in a geometric shape. These effects are most prevalent on the rider's body, in particular the arms and legs.

The reason for this is the so-called 'boundary layer' transition effect. The boundary layer is the small layer of fluid, in this case air, directly on the surface, increasing from zero velocity on the surface, up to the freestream air velocity. At cycling speeds, the boundary layer can be typically around 1 to 4 mm thick depending on the distance along the object and the speed. The boundary layer can have two states. At lower speeds, it is laminar (the flow in the boundary layer is smooth and parallel to the body surface) and at a certain speed there is a transition, and the boundary layer becomes turbulent (the flow in the boundary layer is mixing and not parallel to the body surface). The distance which the air travels along the surface also plays a role. Typically, the boundary layer begins in a laminar state and after a certain distance (which is also dependent on the speed), it will naturally transition to a turbulent state. It is this boundary layer transition from a laminar to a turbulent state, that for certain geometries, can lead to significant changes in the overall flow field and the overall Cd of the body.

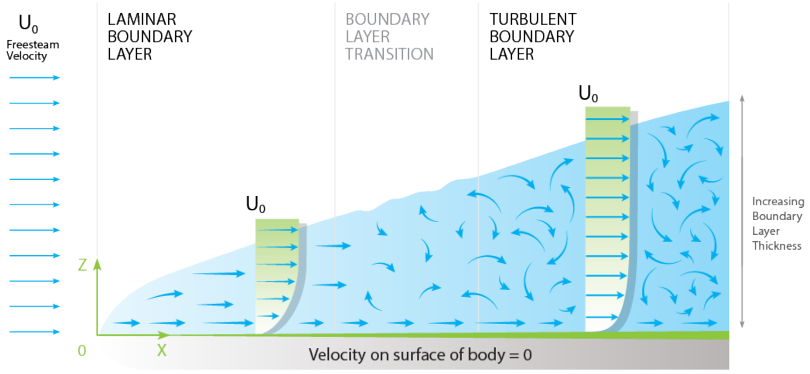

Figure 2: The boundary layer transition effect along a body`s surface.

Factors affecting this transition are described by the Reynold number equation.

Re = ρ * U * L / μ

ρ = fluid density
U = fluid speed
L = a characteristic dimension of the body, for example, the diameter of a cylinder
μ = dynamic viscosity of the fluid

In cycling, this effect can be very important for aerodynamic drag performance. Although a turbulent boundary layer has more drag than a laminar one, the mixing effect of the turbulent boundary layer, draws higher energy air to the surface of the body. This helps the air flow remain attached to the body for longer, delaying the flow separation and thereby reducing aerodynamic drag.

As an example, the air flow around circular cylinders and other bodies with curved surfaces, can show significant changes in the large-scale flow structure for a small change in air speeds and/or cylinder diameter. On cylinders, this can result in drastic changes in aerodynamic drag with reductions of more than 50% possible. This has been well documented in literature and are governed by the Re number equation.

It just so happens that the geometry of human calves, rider speeds, and typical properties of air are close to a critical Re number where the boundary layer transition can be influenced, in particular by surface roughness and the level of turbulence in the air.

The turbulence level in the air is not controlled by the athlete, however, the surface roughness of the body can be modified by fabric selection. Through fabric selection these surface flow mechanisms can be manipulated, directly 'tripping' the boundary layer to a turbulent state at the most opportune position on the body to encourage flow attachment, thereby generating Cd improvements at the same air speed and without changing the geometry of the calves. This is the underlying mechanism behind the Swiss Side aero calf sleeve project.

The human calf has geometries similar in some ways to circular cylinders and it is instructive to use a circular cylinder with a diameter of a typical calf width, as a simplified starting point in this investigation.

The figure below shows the CdA of a 100mm diameter cylinder measured with speed steps from 4 to 20m/s (14 to 72 km/h) in the Swiss Side wind tunnel. The cylinder was tested with a smooth surface (orange trace) and 3 different fabrics (red, green, and blue traces). The smooth surface (orange trace) shows a CdA that decreases slightly with speed. The 3 different fabrics (red, green, and blue traces) at the low speed have a similar CdA value to the smooth surface but with increasing speed show considerable differences in CdA both with the magnitude of CdA reduction and speed at which the CdA reduction occurs at. The greatest reduction in CdA is with the blue trace showing a CdA reduction of 60% compared to the smooth surface. This indicates the potential for aerodynamic gains.

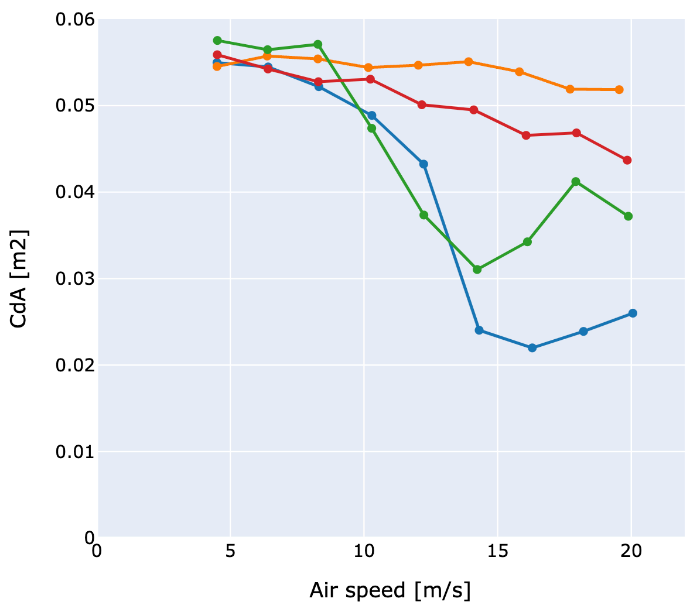

Figure 3: CdA of a 100mm cylinder at speeds ranging from 4 to 20m/s in the Swiss Side wind tunnel.

It is important at this point to recognize the differences between a circular cylinder tested in a wind tunnel and a human calf geometry in a dynamic riding condition:

a) The calf is a loose approximation to a circular cylinder in that the cross-section of the calf is not a circle and the dimension of the cross-section dimensions change between ankle and knee. Also, to be mentioned is that each athlete will have their own individual calf geometry. Furthermore, the actual calf geometry will vary around the crank rotation as the muscle loading changes.
b) The calf is moving such that the air flow angle of attack changes continuously through the crank rotation. This leads to considerable changes in the air flow angle onto the calf. The calf “axis” can vary from 15 to 50 deg in one crank revolution.
c) The rotation of the crank not only changes the onset flow angle but also imposes a dynamic velocity on the surface of the calf which influences the flow field and boundary layer characteristics.
d) The calf will be exposed to natural turbulence in the air and turbulence generated by the bike itself.

From the above, we can appreciate the potential for drag reduction based on circular cylinders but are aware of the differences between circular cylinders to human calves in a real-world riding situation.

Due to the complexity of the problem, it was considered that no optimum fabric could be defined just through theory and that a range of fabrics would need to be physically tested and characterised, using multiple testing methods.

2. DEVELOPMENT METHODS

Swiss Side needed to find methods to be able to assess the aerodynamic benefits of a wide range of fabrics in an accurate and practical manner.

The following is a list of methods employed by Swiss Side, with benefits and limitations noted for each:

a) Fabric testing on fixed circular cylinder

Benefits:

- Fundamental starting point measurement for classifying fabric performances.
- Can be tested in Swiss Side in-house wind tunnel over a wide range of speeds with high measurement accuracy and high efficiency, allowing a large number of tests in a time and cost-effective manner.
- Turbulence can be introduced in a controlled manner in the Swiss Side wind tunnel, to understand the real-world (non-laboratory) airflow turbulence impact on the results.

Limitations:

- Shape difference of a circular cylinder to generic calf shape.
- No dynamic motion of the geometry to airflow.

More than 50 fabric types were evaluated in this way with speeds in the range of 14 to 72km/h on cylinders of two diameters.

b) Fabric testing on calf geometries

Benefits:

- Real calf geometries measured from athlete.
- Can be tested in Swiss Side in-house wind tunnel over a wide range of speeds with high measurement accuracy and high productivity allowing a large number of tests in a time and cost-effective manner.
- Turbulence can be introduced in a controlled manner in the Swiss Side wind tunnel
- The influence of flow yaw angle can be measured (as experienced by an athlete in real-world conditions with wind).

Limitations:

- No dynamic motion of the geometry to airflow, although each geometry was compared at two leg orientations.
- The influence of the bike or rider on the flow field around the calf is not included.

More than 40 fabric types were evaluated in this way with speeds in the range of 14 to 72km/h on both left-hand and right-hand calves (at two leg orientations).

c) Full-size wind tunnel testing with fixed-leg mannequin

Benefits:

- Testing with the complete bike rider geometry ensures greater flow field accuracy (the calf geometries are identical to those used in the Swiss Side wind tunnel calf tests).

Limitations:
- Testing in the full-size wind tunnel is more costly and with reduced availability compared to Swiss Side inhouse wind tunnel.
- Lower testing efficiency leading to less options tested and a narrower speed band.
- Reduced drag force measurement resolution compared to Swiss Side in-house wind tunnel.
- No dynamic motion of the legs, although the static leg results can apply for coasting or descending scenarios when the rider does not pedal.

14 fabric types were evaluated in this way with speeds from 30 to 45km/h.

d) full-size wind tunnel testing with athletes

Benefits:
- Testing with fully representative athlete calf geometries
- A range of athletes of different sizes gives a range of calf geometries
- Inclusion of dynamic moving legs through rider pedaling
- With an athlete we are comparing fabric material to athlete skin (and not to the surface roughness of the plastic test geometry of the mannequin)

Limitations:
- Reduced drag force measurement resolution due to athlete repeatability

5 most promising fabric types from tests a), b), and c) were evaluated in this way with speeds from 30 to 45km/h.

e) Road tests with athletes

The on-road measurement of aerodynamic drag coefficient was made using the Swiss Side CdA Meter. This step is an important correlation step to ensure improvements measured in the wind tunnel are also measured on the road.

Benefits:
- The most realistic real-world conditions including the effect of turbulence in the air

Limitations:
- More time-consuming than wind tunnel testing.
- Reduced drag force measurement resolution due to athlete repeatability and real-world effects on the measurement system compared to the more controlled environment of wind tunnel testing.

4 fabric types were evaluated in this way at a range of speeds from 30 to 45km/h.

Additional test methods included:

- In some cases where the fabric was not isotropic, the orientation of the fabric to the geometry was changed.
- Some cases were tested with different levels of turbulence in the airflow.
- Some cases were tested in yaw angle steps between -20 and +20 degs.

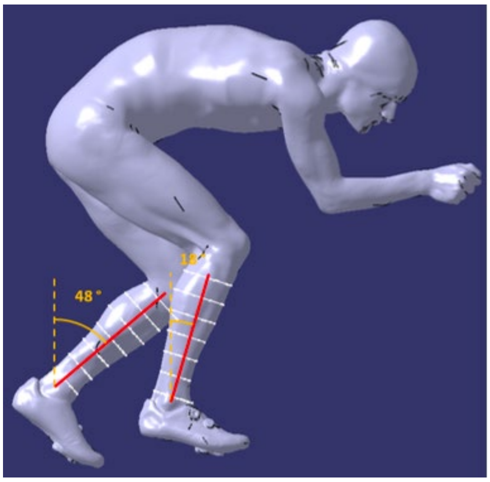

Figure 4: The mannequin used and geometrical details of the calf + foot region used for the tests in the Swiss Side wind tunnel.

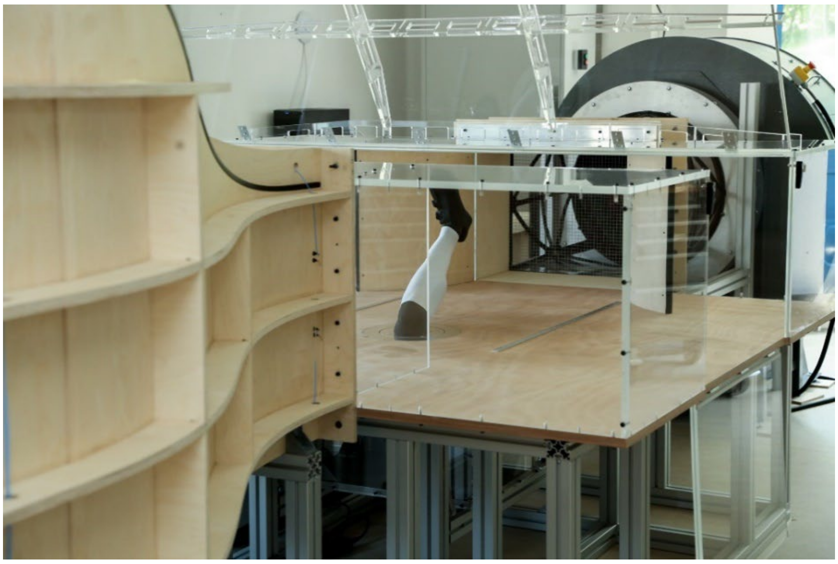

Figure 5: General image of the Swiss Side wind tunnel.

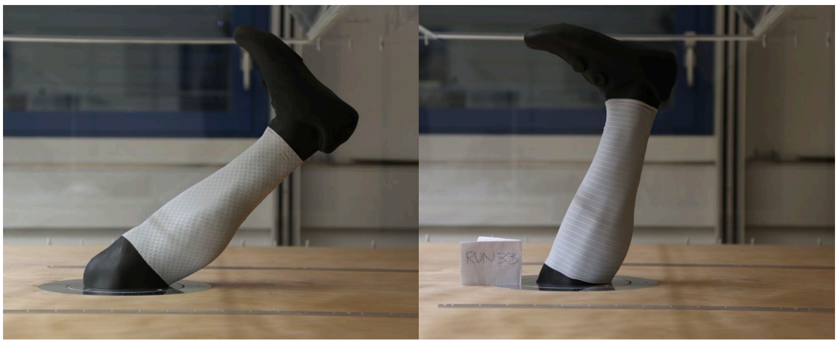

Figure 6: A typical fabric testing with right-hand and left-hand calf orientations in the Swiss Side wind tunnel.

Figure 7: Mannequin testing with the AERO CALF Sleeves in the full-size wind tunnel.

Figure 8: One athlete of the many tested with the AERO CALF Sleeves in the full-size wind tunnel.

Figure 9: Real world measurements with CdA meter.

3. PERFORMANCE CRITERIA

Throughout the process, the aim was to produce AERO CALF Sleeves that delivered strong CdA reductions over a wide range of athletes (calf sizes) and speeds. The ranking of performance for the calf tests in the Swiss Side wind tunnel was based on a weighting system. The weighting system rewards the results based upon how often each speed occurs in typical triathlon races. In this way, it is ensured that the performance benefit is delivered at realistic speeds seen in the real world.

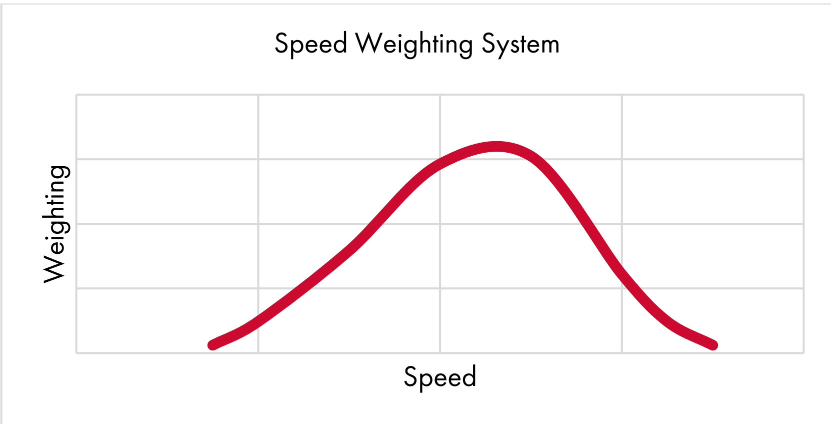

Figure 10: Speed Weighting System Schematic of speed frequencies in triathlon races.

RESULTS

1. SWISS SIDE WIND TUNNEL

The circular cylinder testing was used as an initial learning process for the fabric options and as a filter for the more representative calf tests in the Swiss Side wind tunnel. The CdA reduction from fabrics on the calves was generally less than that from the same fabric on circular cylinders. The CdA reduction from fabrics on the vertical calf was generally greater than on the rearward angled calf orientation.

For the calf tests performed in the Swiss Side wind tunnel, the right-hand and left-hand calves (at two leg orientations) were weighted based on speed as described above and then averaged to give a single CdA value.

The plot below shows the CdA change for 45 aero calf sleeve options compared to no sleeve (written as None) with results shown for the left-hand calf only (orange trace), the right-hand calf only (grey trace), and the average of both calves (blue trace). The results show significant performance variation with on average some sleeves being worse than no sleeve and some sleeves showing much greater variation between left-hand and right-hand calves than others. In these situations, we favored the sleeves that were more consistent in performance left-hand to right-hand as it was felt this may lead to greater consistency across different athletes.

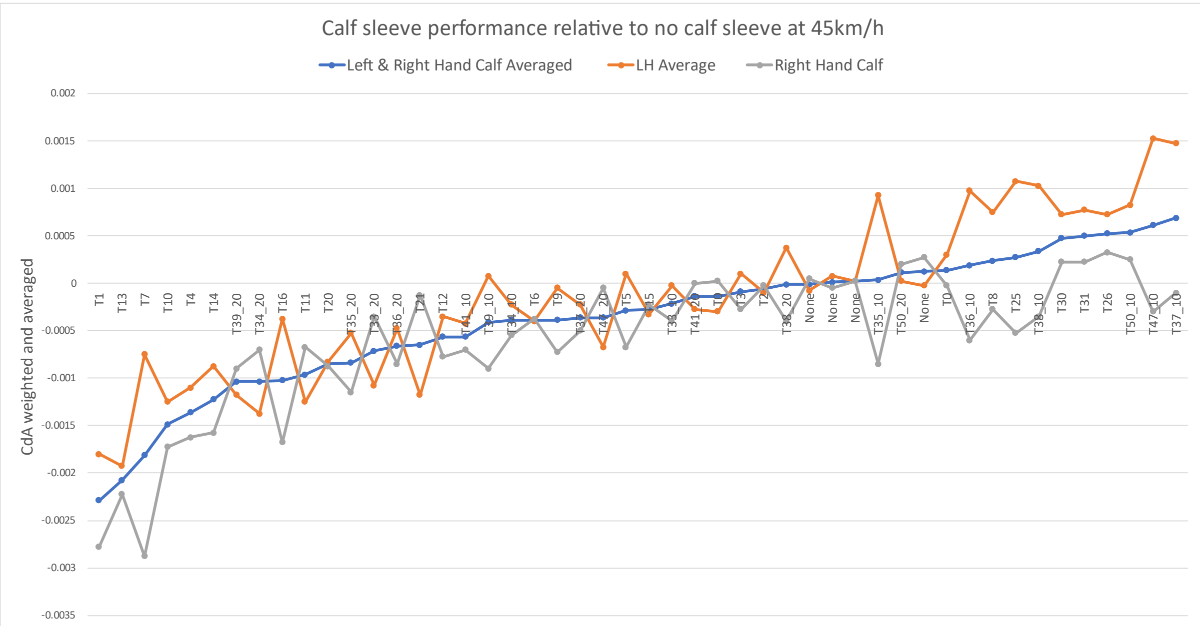

Figure 11: Calf sleeve performance relative to no calf sleeve at 45km/h.

Of interest was the fact that not one fabric was best for both the right-hand and left-hand calves. This highlights the challenge of developing the calf sleeves in that the required level of roughness and therefore fabric choice is highly dependent on the orientation of the calf to the airflow. Separate tests with inclined oval cylinders confirm this. This further confirms that one fabric is not optimum for all calf positions.

2. FULL-SIZE WIND TUNNEL MANNEQUIN TESTS

The best options from the Swiss Side wind tunnel calf tests were used in the mannequin testing. The Swiss Side wake measurement system was routinely used to assess the changes in the wake brought about by calf sleeve changes. The wake is measured in a plane directly behind the rear wheel. The total pressure loss in the airflow is measured by 128 probes. This is effectively a measurement of the energy lost in the air flow, which is the aerodynamic drag. In this way, the aerodynamic drag losses are visualised, and the specific area which has changed can be identified. The image below shows a measurement with the system, in this case with an athlete in a standard triathlon setup, without the calf sleeves:

Figure 12: Aerodynamic measurements in a full-size wind tunnel on athlete without AERO CALF Sleeves. The red zone indicates no losses (100% total pressure). The darker the blue, the more the losses/aerodynamic drag.

The wake is also displayed in the data analysis system as contours of total pressure coefficient. The smaller the contour number the greater the losses. In the image below, the blue traces are with no calf sleeve, the orange with sleeve. Here we see the orange contour lines (with sleeve) are displaced closer to the center line in the region where the rider's calves are (0.5m above the ground) compared to the blue lines (no sleeves) indicating reduced losses in the wake in the region where the sleeves have an effect.

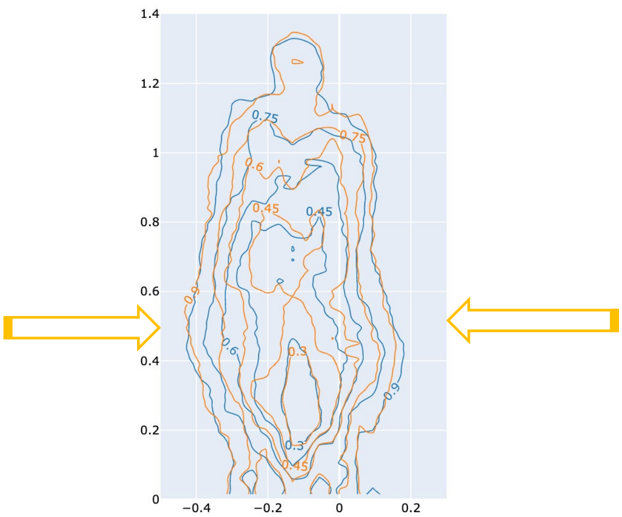

Figure 13: Axis Z shows the height above the ground, axis Y shows the lateral position. The improvement brought by sleeves is most visible in the 0.3, 0.45, and 0.6 pressure contours.

The mannequin tests showed generally similar results to that found in the Swiss Side wind calf tests, but the order of performance was different. Thus, the calf test measurements from Swiss Side wind tunnel tests proved to be a sound basis for pre-selecting the best options for full-size wind tunnel testing.

The most interesting options from the mannequin (and the Swiss Side wind tunnel calf tests) were selected for athlete testing. This resulted in 5 calf sleeve options tested compared to the reference without sleeve (bare skin), tested on 3 athletes with rotating legs at 37.5km/h and 45km/h. The optimum sleeve was the only sleeve that gave a performance improvement for all riders at both speeds and was considering all 3 riders the best sleeve at both the 37.5km/h and the 45km/h speed.

In the early stages of the calf sleeve development, it was anticipated that different optimum sleeve fabrics would be needed for the lower speed compared to the higher speed. However, the best-performing fabric from all the options tested was found to be the optimum at both speeds.

A fabric can have roughness from the weave (fine-scale roughness) and roughness from larger dimension structures in the fabric (large-scale roughness). There are many ways within the structure of the fabric to achieve a desired layer of roughness. Different arrangements of roughness components in the fabric will lead to different types of turbulent boundary layers. Too little turbulation from the roughness features may not be adequate to impact the boundary layer. Too much turbulation can then add too much disturbance and lead to increased drag. Therefore, finding the right level of turbulation from the roughness features, which can be based on size or orientation but also the position on the aero sleeve, makes for a very complex challenge.

Figure 14: Fabric sample T13 in an early prototype phase in full-size wind tunnel with an athlete.

Interestingly, this sleeve (sample T13 also shown in figure 11graph and the image above) had stripes as the primary roughness features orientated in the horizontal plane around the circumference of the calf. This fabric had also been tested with the stripes in the vertical orientation and was found to be inferior in performance. Why this would be is not immediately obvious but when the orientation of the calves to the oncoming airflow is considered then the horizontal stripes when being ridden are never actually horizontal and are always presenting an angle to the oncoming flow, which then varies depending on the crank rotation.

3. ROAD TESTS

The final confirmation test was made on the road where the change in CdA with a small selection of calf sleeves was measured. Here the improvements for the selected sleeves were confirmed, falling within the range of measurements from the athlete tests in the wind tunnel.

4. FULL-SIZE WIND TUNNEL TESTS OF PROTOTYPE SLEEVES WITH ATHLETES

A pre-production version of the selected calf sleeves was prepared and this showed to be equivalent in performance to the test version. Further tests were made with athletes in the full-size wind tunnel leading to the evaluation of the selected production specification calf sleeves on 13 athletes. The tests showed performance improvements for 12 of the 13 athletes with the greatest drag reduction amounting to 8W saving at 45km/h compared to no sleeve. The average for all 13 athletes was 4W saving at 45km/h compared to no sleeve.

ABOUT SWISS SIDE

Established in 2011, the Swiss Side brand was a spin-off from Formula 1 motorsport, based on co-founder Jean-Paul Ballard's 14-year long F1 career, with purpose to transfer the closely guarded know-how to the cycling industry, particularly when it comes to aerodynamics and physics. Today, Swiss Side is a proven industry leader in developing the best performing aerodynamic cycling & sports products, having developed world-wide leading know-how and R&D infrastructure for low-speed aerodynamics. The fruits of this can be found not only in products under the Swiss Side brand but also those developed in collaboration with some of the biggest brands, athletes and teams in these industries.