

# Flow Visualisations in Sports

by Wouter Terra  
and Andrea Sciacchitano

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## Colophon

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## Cover photo

Oil flow visualisation is used to determine the main areas of flow separation on the body of a skeleton athlete model at 100 km/h in a wind tunnel. Separation lines are clearly visible around the armpits, as illustrated by the thick, bright green lines of accumulated fluorescent oil illuminated by UV light.

## Why innovation in sports matters

Innovation and sports have been linked for as long as competitive sports exists. Some of the most well-known examples are the futuristic track bike that Chris Boardman rode at the '92 Olympics, and the "klap-skate" that made skaters crush all standing world records in the timespan of only two years around 1998. TU Delft, and specifically the Department of Aerospace Engineering, has been involved in numerous innovations applied at the highest level of sport. The most recent examples in the field of sports and aerodynamics can be found in this book, including innovations in road cycling, track cycling, speed skating and skeleton.

## TU Delft Sports Engineering Institute

The recent innovation projects in this book have been developed in close cooperation with the TU Delft Sports Engineering Institute. This institute was launched in 2014 to spark multidisciplinary collaboration in the field of sports, and create structural partnerships with sports federations and companies working in the field of sports. It is because of this structural collaboration between with National Olympic Committee, Sports Federations and commercial cycling teams like Team DSM that we have been able to create innovation projects that truly made a significant difference in elite sports.

## Competitive advantage and societal impact

In front of you lies a booklet with some great examples of how the latest scientific knowledge in Aerospace Engineering has been applied in elite sports. However, with this application of knowledge in elite sports we do not only try to give our athletes a competitive advantage. We also create a convincing showcase of how technology can solve problems and use the knowledge that has been developed for elite sports to tackle societal challenges. For example, new on-site measurement techniques for speed skaters can also be applied to make cars more efficient. And the same principles of bicycle dynamics that have been used to create the faster track bike, can be used to prevent elderly from falling with their e-bike. That makes sports innovation a win-win concept for both sports and society. Enjoy reading!

**Daan Bregman**, Business Director, Sports Engineering Institute

# Introduction

In many sports, fluid mechanic forces play an important role in the performance of athletes. In some sports such as cycling and speed skating, the aerodynamic drag is the main contributor to the overall resistance. Hence, its minimisation is key to enhance the athletes' performance. Adversely, in ski jumping the lift force, in combination with the aerodynamic drag, determines the length of the jump. From a fluid mechanics perspective, optimisation of the stroke of a swimmer is possibly even more complex. The hydrodynamic forces are responsible for the generation of thrust and thus the athlete's forward motion. At the same time, these forces produce the drag that pulls the athlete backwards. Fluid mechanics is obviously also relevant in many ball sports such as baseball and football, where the aerodynamic forces affect the trajectory of the ball. This collection of visualisations focuses on the flow around the human body in sports where the athlete interacts with air or water.

*"At TeamNL, we continuously work on development. To do so, we need the expertise of partners like the TU Delft Sports Engineering Institute. In 2018, we started a structural collaboration on the optimisation of aerodynamics in the programs of TeamNL. Aerodynamics are absolutely crucial in sports where speed is key and differences between competitors are small. We compete at the edge of our capabilities, where every 1/100th of a second counts. Together with the Sports Engineering Institute, we make aerodynamics work for us!"*

## **Kamiel Maase**

Performance Manager  
Sport Science & Innovation,  
TeamNL Experts  
NOC\*NSF Topsport

In sport research, the goal is often to optimise the fluid dynamic forces, typically by minimising the drag or maximising the propulsive force. This may be achieved by 'trial and error' in wind tunnel tests measuring the loads with force balances. The latter can accurately provide the resultant loads exerted by the fluid, but they do not reveal the fluid motion around the athlete. Understanding the flow topology and relating it to the fluid mechanic loading, is key to optimise the athlete's posture and equipment and thereby enhance his or her performance. For this purpose, different flow visualisation and measurement techniques are available. These vary from qualitative techniques such as smoke plumes used in wind tunnels, to quantitative techniques that allow the measurement of the fluid motion in gasses as well as liquids (e.g. particle image velocimetry; hotwire anemometry).

This brochure contains a collection of flow visualisations of four sports in which fluid mechanics is crucial: cycling, speed skating, skeleton and swimming. Throughout this document, flows around athletes' bodies are presented, visualised or measured by different flow visualisation techniques. With this collection of images, the authors aim to provide an impression of the beauty and complexity of the flow topology in these sports. By no means they have the aim to give a comprehensive description of these phenomena. Apart from this general introduction, written text in this document is kept to the bare minimum, giving priority to the flow visualisations. At the beginning of each chapter, a short introduction provides the background of the specific sport from a fluid mechanics perspective. Additionally, short descriptions are given with each illustration, explaining the depicted flow structures and the measurement technique used.

We hope that these visualisations will provide new insights and inspire readers, leading to new research in sports fluid mechanics.

# Cycling

In cycling, only a small portion of the total resistance comes from rolling resistance. By far the larger part stems from the interaction with the air, sometimes over 90%. To reduce this aerodynamic drag, it is crucial to understand the different, complex airflows around a cyclist. For instance, the air that passes around the arms affects the airflow around the legs and possibly vice versa as well. Furthermore, the cyclist is pedaling so the legs are constantly in motion and changing orientation. And most importantly, the bluff shape of the human body makes it difficult to predict - and ideally control - when and where the air will separate from its surface.



1.

## Streaks of small bubbles around a cyclist

The airflow around a cyclist is visualised by injecting small helium-filled soap bubbles (HFSB) into the wind tunnel. The helium is added to make sure the bubbles accurately follow the direction of the airstream. The bubble streaks show us how the air passes over the back of the cyclist and visualises the formation of a turbulent and swirling downstream flow.

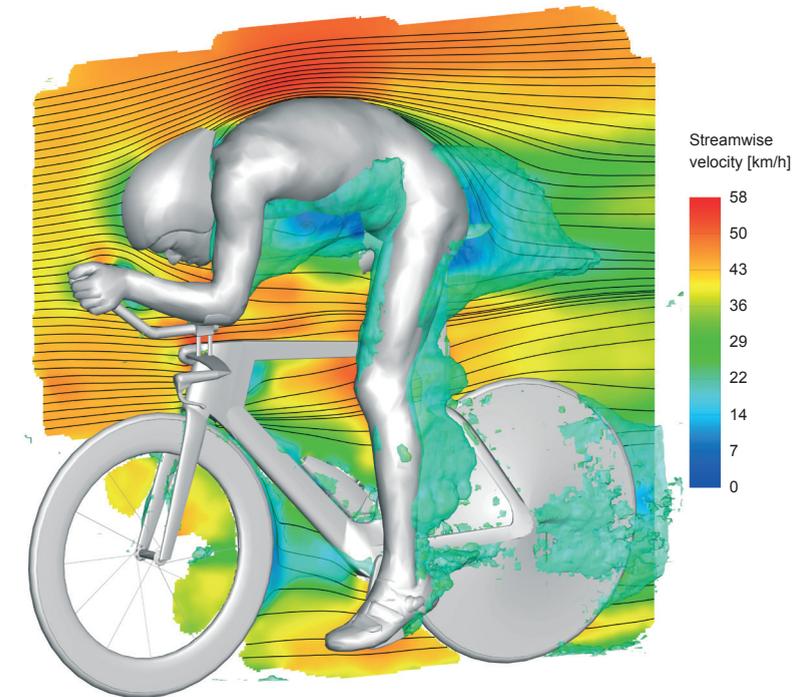
## 2.

## The air stream in front of a cyclist

In contrast to the turbulent flow field in the wake of the cyclist, the approaching airflow is hardly affected by flow separation. This is observed in the parallel HFSB-streamlines which are only deflected by the presence of the rider and the bike. These images were taken during measurements using a state-of-the-art Particle Image Velocimetry (PIV) system [1]. The technique of PIV relies on the velocity measurement of flow tracers immersed in the air to measure the velocity of the air itself. These tracer particles are generally illuminated by a laser and imaged by digital cameras. The present PIV system integrates four cameras and a laser into a single probe operated by a robotic arm, allowing to measure the flow all around the cyclist in a time-efficient manner.

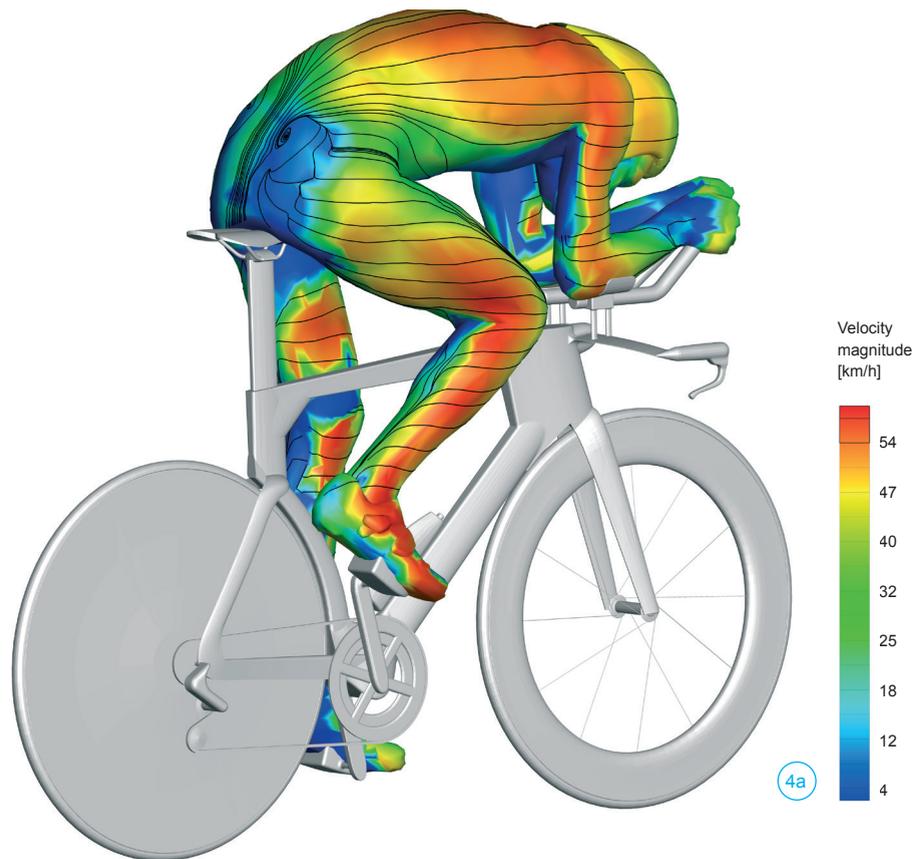
*“For LaVision, as a provider of fully integrated measurement systems for fluid dynamic research, the research performed at TU Delft is of great importance. It provides acceptance of these new measurement systems not only for sports flow measurements but also for other novel application areas. The research has shown that these systems can perform well even in very challenging measurement setups. We benefit from the practical experiences gained in these complex measurement campaigns, which have been on the cutting-edge of the available technology.”*

**Bernhard Wieneke**  
Managing Director,  
LaVision GmbH



## 3. The flow around a cyclist

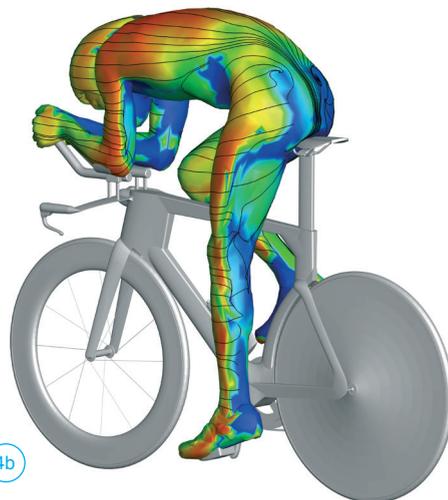
For the first time, the entire flow around a cyclist has been measured in a wind tunnel. This has been achieved using robotic volumetric PIV. The different colours in this visualisation indicate different levels of air velocity in the riding direction of the cyclist. The air streamlines are depicted in black. We observe many, large regions of decelerated air (marked in green), among others behind the legs and lower back. In these areas, the air velocity is less than half of the speed of the cyclist. Such deceleration indicates high production of aerodynamic drag.



4a

#### 4. Velocity near the cyclist's surface

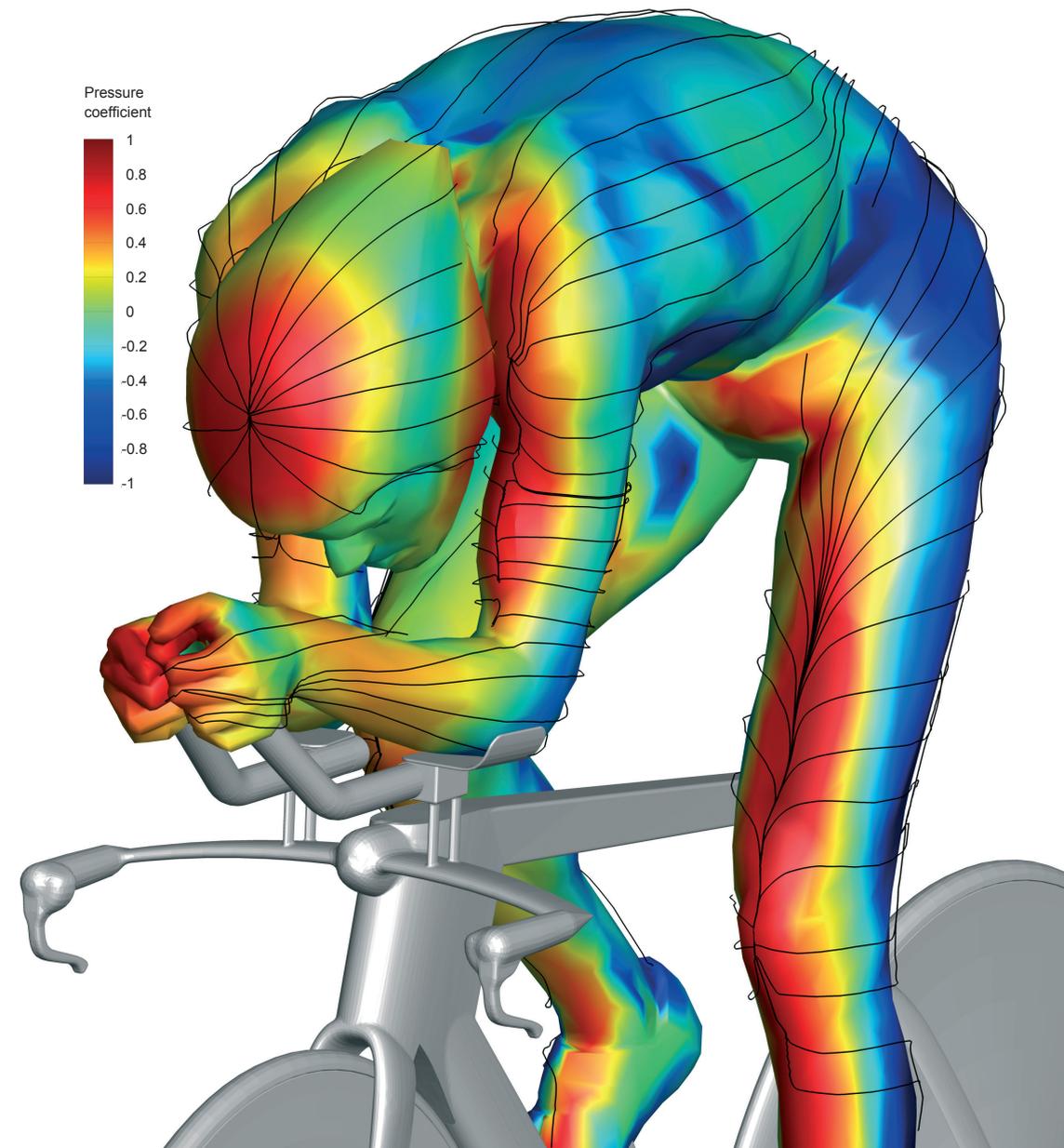
The flow around the cyclist is projected onto a virtual surface very close to the rider (5 mm distance). The velocity magnitude is depicted in colour, the skin friction lines are marked in black. Regions of low velocity (marked in blue) indicate detached flow. The flow detaches from the cyclist's surface when skin friction lines are interrupted. In figure 4b this can be clearly observed all along the left side of the stretched leg. Apart from the flow deceleration, accelerated flow is also present, for example over the back of the rider (velocity marked in red) [1].

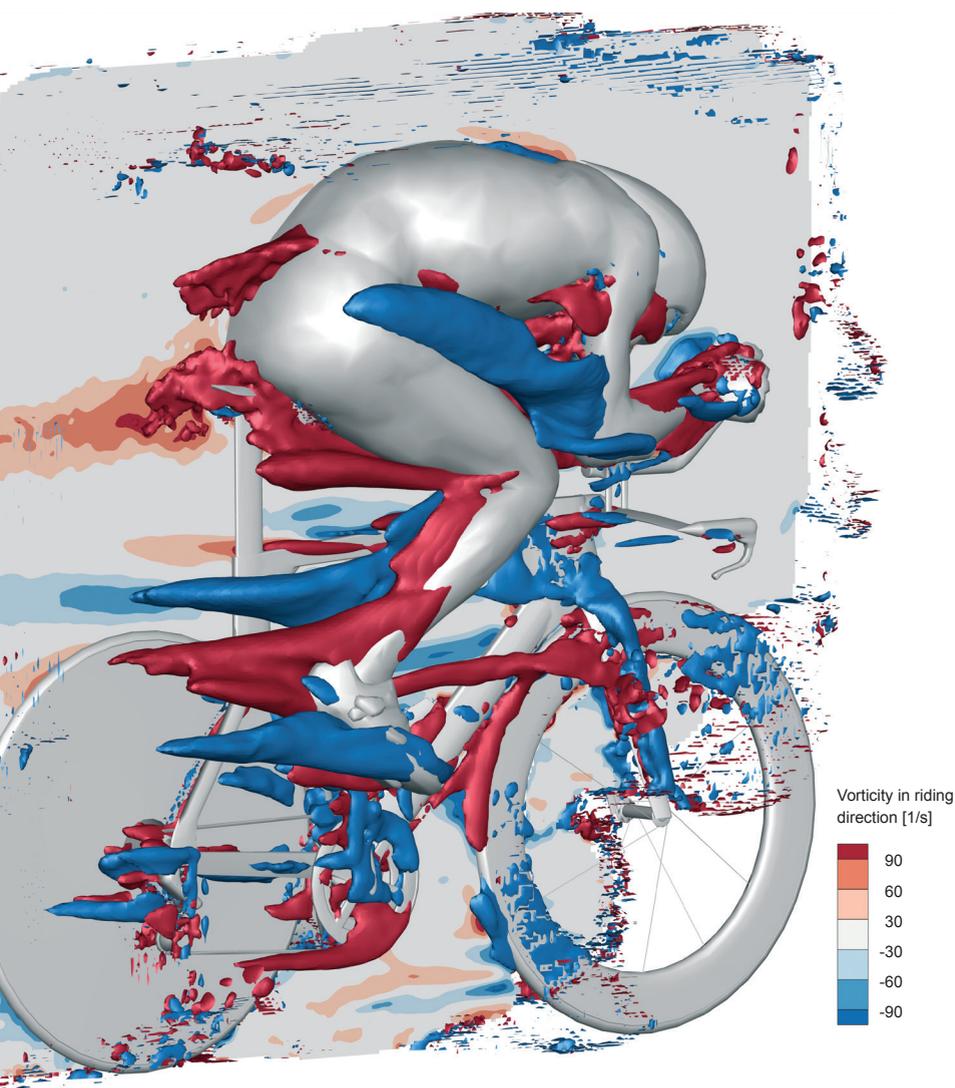


4b

#### 5. Pressure on the cyclist

By far the largest part of the cyclist's aerodynamic drag is caused by the pressure forces acting on the cyclist. The difference between the (red coloured) high pressure acting on the helmet, shoulders and upper legs and the (blue coloured) low pressure acting on the lower back and hamstrings, pulls the cyclist backwards. The pressure forces shown here, have been computed from the measured velocity around the rider that is presented on the previous pages [2].





## 6 Rotating flow around a cyclist

Rotating or swirling flow is often an indication of the generation of aerodynamic drag. Particularly in the flow around the cyclist, the vortices that originate from the rider's thighs and lower back are strongly related to the generated air resistance. The rotation in the direction of motion of the cyclist is visualised here by vorticity: clockwise rotation in red and counterclockwise rotation in blue. This streamwise vorticity is computed from the measured velocity [1].

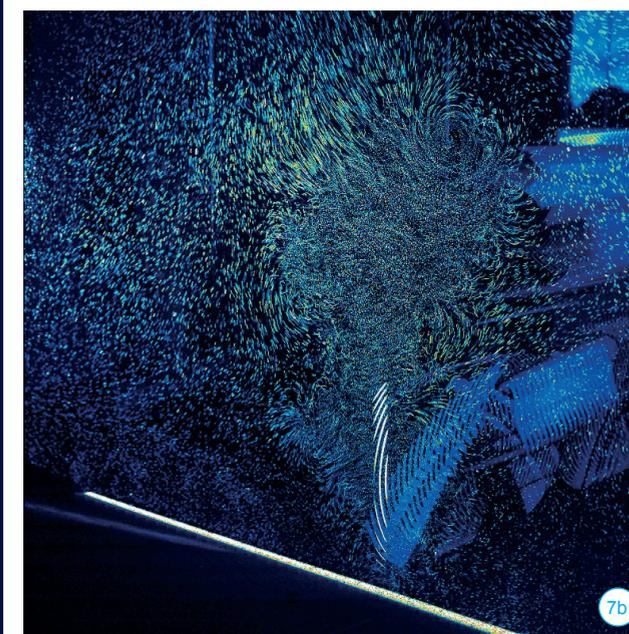
## 7 Ring of Fire flow visualisations

In contrast to measurements in a wind tunnel, the Ring of Fire is a unique system that can measure the flow around a cyclist in the training environment of the athlete. The aerodynamic drag is derived from the measured velocity. Helium-filled soap bubbles (HFSB), imaged and illuminated at high frequency, are depicted in a plane that intersects with the trajectory of the cyclist. Swirling flow, for example behind the tail of the time-trial helmet, is visualised showing an aggregation of a large number of consecutive images (Figure 7b) [3].



*"Within Team DSM we very much value our long-term partnership with the TU Delft. Working together on innovative projects such as the Ring of Fire helps us to stay ahead of the game and gives additional knowledge in the Team that gives us a competitive advantage. As aerodynamics plays a highly significant role in modern cycling, it is very important to understand the characteristics of the flow around a (group of) cyclist(s) which the Ring of Fire can provide."*

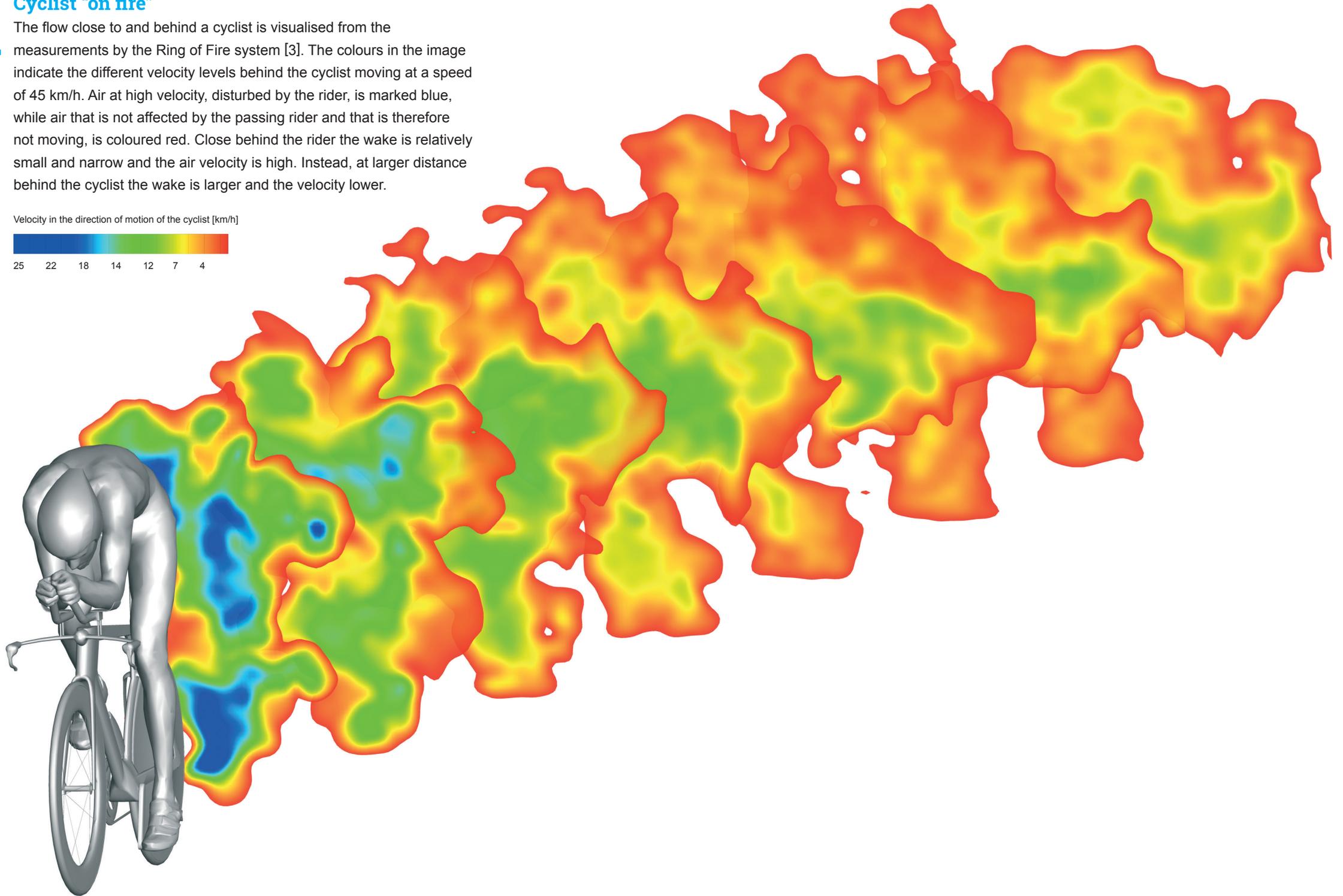
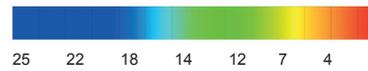
**Harm Ubbens**  
Aerodynamic Expert  
Team DSM



## 8 Cyclist "on fire"

The flow close to and behind a cyclist is visualised from the measurements by the Ring of Fire system [3]. The colours in the image indicate the different velocity levels behind the cyclist moving at a speed of 45 km/h. Air at high velocity, disturbed by the rider, is marked blue, while air that is not affected by the passing rider and that is therefore not moving, is coloured red. Close behind the rider the wake is relatively small and narrow and the air velocity is high. Instead, at larger distance behind the cyclist the wake is larger and the velocity lower.

Velocity in the direction of motion of the cyclist [km/h]



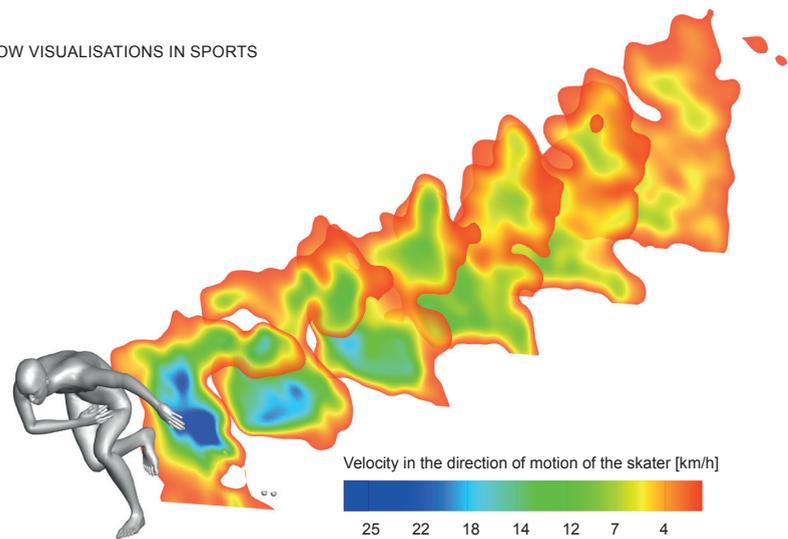
# Speed Skating

Speeds in skating can reach up to 65 km/h, making it the second fastest human powered form of transportation, after cycling. As in cycling, the aerodynamic drag in skating dominates the overall resistance. Because the body posture of a skater somewhat resembles that of a cyclist, it is not surprising that the flow around these different athletes shows quite some resemblance, both causing a large, turbulent and swirling wake. In contrast to cycling, the skater's trajectory on the ice is not straight. The body of the athlete moves harmonically from left to right, whilst changing body posture accordingly. As a consequence, it is very challenging to characterise the flow around a skater. Ideally, we measure the flow throughout the entire skating stroke in order to relate the changing stream of air to the variation in aerodynamic drag.



## 9. Streaks of soap bubbles around skaters

The streaks of helium-filled soap bubbles (HFSB) in these figures are obtained illuminating a plane intersecting the skaters' trajectory and taking relatively long exposure images. In the chaotic airstream following the passage of a skater, large coherent swirling structures are observed. The images were taken by a photographer moving alongside with the skaters during a measurement campaign with the Ring of Fire system at the Thialf ice rink in Heerenveen, The Netherlands [4].

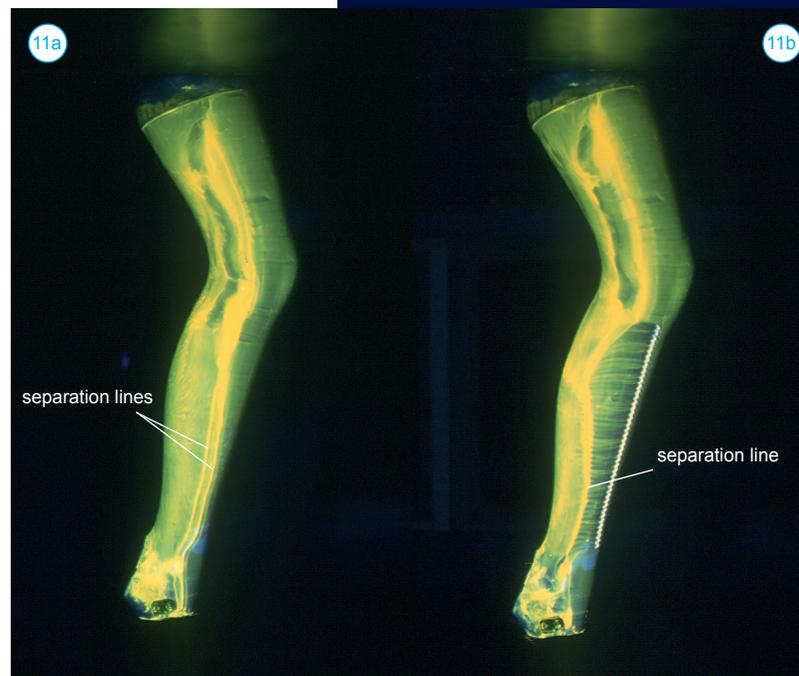


## 10. A snapshot of a skater's wake

The shape of the air velocity distribution behind a skater changes significantly with the phase of the skating stroke. In the current phase, where the athlete is just about to place his right skate on the ice, the air downstream of the swinging left arm has clearly been accelerated into the direction of motion of the skater. This is most evident in the plane closest to the athlete, which is about 50 cm behind the skater's lower back. This visualisation has been obtained through Ring of Fire measurements on an athlete moving at 40 km/h.

## 11. Low-drag with zig-zag strips

The legs of a skater generate a relatively large amount of drag caused by the early flow separation. The separation line is visualised using fluorescent oil on the surface of the leg and illuminating the oil with a UV lamp [5]. The oil accumulates at lines of flow separation. By placing zig-zag strips on the leg (figure 11b), this separation can be moved backwards. This disturbs the flow and reduces the aerodynamic drag.



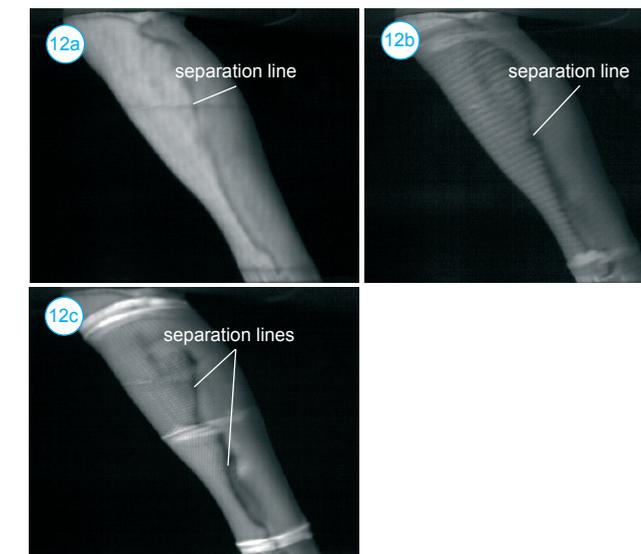
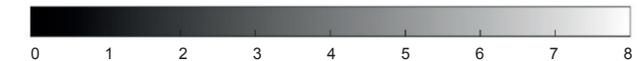
*"The collaboration with the TU Delft has given a boost to the innovation of the skate suits that SportConfex develops for the KNSB and TeamNL. A state-of-the-art suit was made and used at the Beijing 2022 Winter Olympic Games by combining the university's test facilities and aerodynamic knowledge and our experience with expertise on fabrics and the production of garments for pro-athletes. I expect that this collaboration will lead to more innovations in the future."*

**Bert van der Tuuk**  
CEO, SportConfex BV

## 12. Flow control by modification of skate suit fabric texture

As an alternative for using zig-zag strips, the aerodynamic drag of a skater's leg can also be reduced using rough or textured fabrics in the skating suit. Oil flow visualisations over woven and knitted fabrics are typically challenging as the oil is drained into the suit. Instead, infrared thermography is used to visualise the separation lines. This technique relies on the measurement of temperature differences that are caused by the cooling effect of the air around the model. Figure 12a shows a bare, smooth leg. Figures 12b and 12c represent visualisations of the flow past a leg dressed in a single, striped fabric (12b) and one dressed in two different kinds of fabric, one for the lower and one for the upper part of the model (12c). It is clear that the separation line is affected by the different fabrics. It is not so obvious though, whether or not the aerodynamic drag is affected as well.

Temperature difference flow on/off [°C]



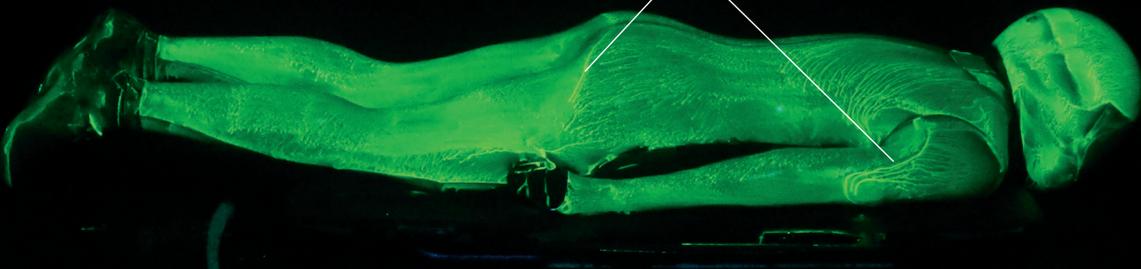
# Skeleton

Lying on a small sled only a few centimes from the ice, skeleton athletes reach speeds well over 100 km/h.

In contrast to a cyclist and a skater, skeleton athletes can take more streamlined positions on their sled. In this way they reduce the aerodynamic drag and optimise their speed. Despite the lying orientation of the human body, large areas of flow separation persist over the body of the athlete. As a consequence, also in skeleton, the aerodynamic drag dominates the overall resistive forces acting on these athletes and their vehicle.

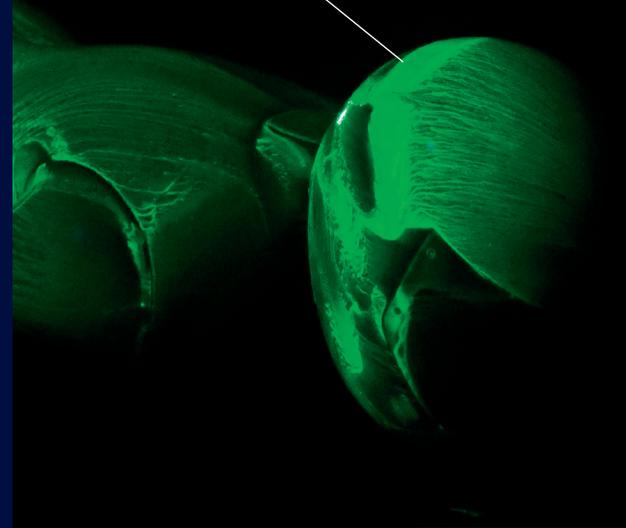
13a

flow separation



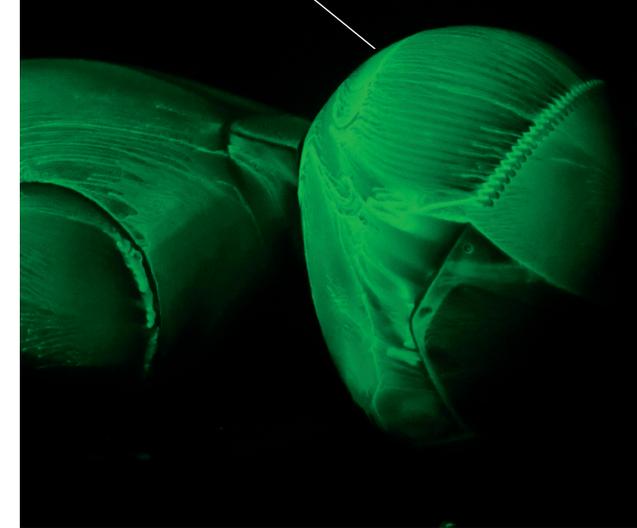
13b

flow separation



13c

flow separation



## 13. Flow separation over a skeleton athlete

Oil flow visualisation is used to determine the main areas of flow separation on the body of a skeleton athlete model at 100 km/h in a wind tunnel. Separation lines are clearly visible around the armpits, over the buttocks and thighs (Figure 13a), as illustrated by the thick, bright green lines of accumulated fluorescent oil illuminated by UV light. Over the helmet, the flow transitions from laminar to turbulent before it separates (Figure 13b). At such high velocity, disturbing the flow through the application of zig-zag strips (Figure 13c) does not postpone the separation and, in that way, does not reduce the aerodynamic drag.

*"Aerodynamics in our sport is very important. Better aerodynamics means you have the ability to accelerate faster than your opponent. Since every athlete is built different this varies from individual to individual. The TU Delft provided me the opportunity to improve my aerodynamics with the effect that I could perform on a higher level. This was one of the contributing factors to my Olympic bronze medal."*

### Kimberley Bos

Dutch skeleton athlete and Olympic bronze medallist

# Swimming

The flow around a swimmer is very complex, possibly even more so than that around skaters and cyclists.

The forces which are exerted on the swimmer's body by the water, are responsible for both the resistive force, slowing him or her down, and the propulsive forces generated by the arms and legs. The fact that there are two fluids immersing the swimmer, both air and water, further complexifies the fluid mechanics problem.

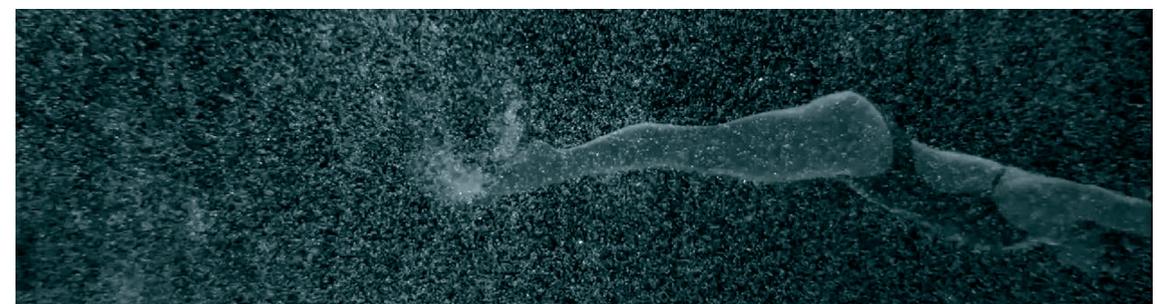
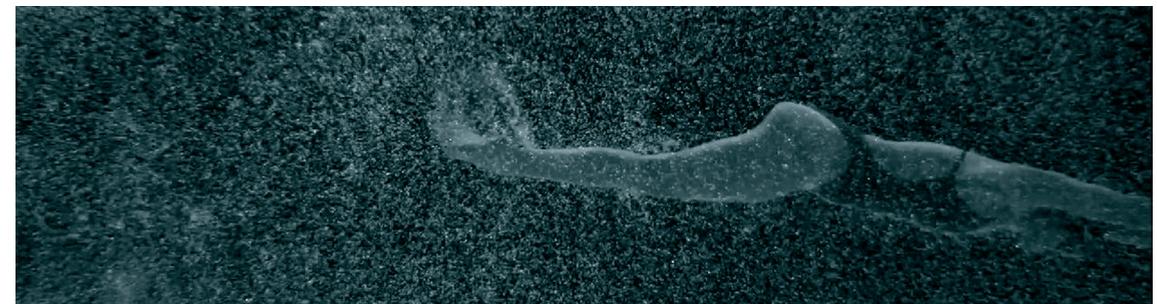
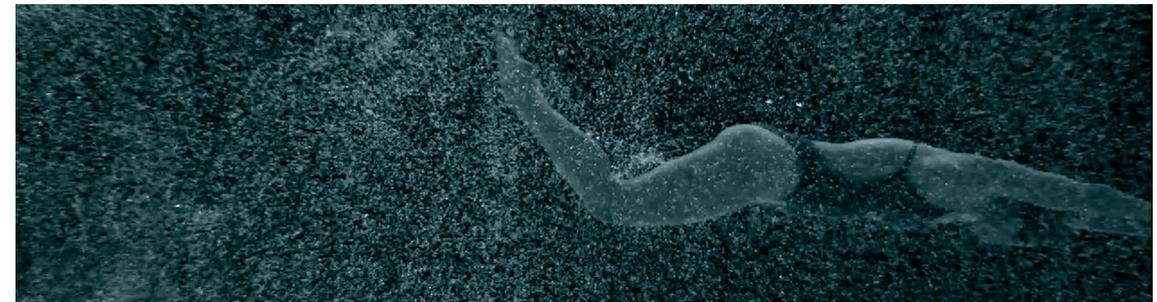
The resistive force acting on the swimmer, for example, consists not only of hydrodynamic drag, but also of wave drag. The visualisations in this section are obtained from experiments in both water and air.

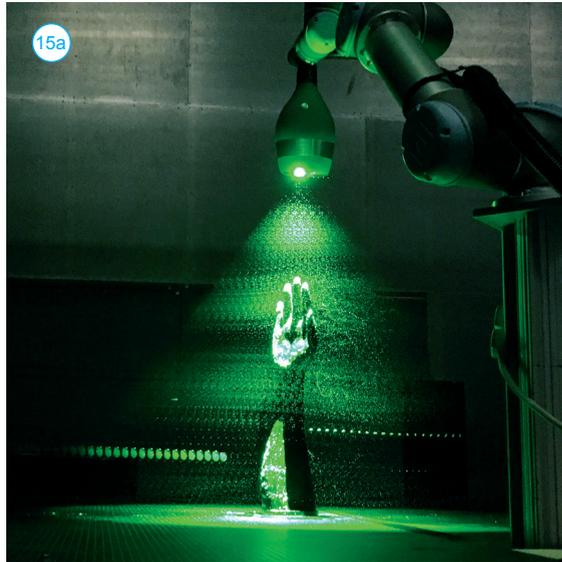
## 14. Water bubbles around a swimmer

The flow around a swimmer is visualised through a unique Particle Image Velocimetry system that can be installed in a regular swimming pool [6]. The PIV system uses small air bubbles injected into the water from the swimming pool floor and cameras installed on its walls.

These rising bubbles, observed as bright dots in the images, are disturbed by the passing swimmer. The velocity around the swimmer's body (not depicted here), is obtained using synthetic aperture PIV.

With each kick of the feet, a pocket of water is propelled downwards, accompanied by a counter-rotating vortex pair. These swirling water pockets move downwards as the athlete moves forward.



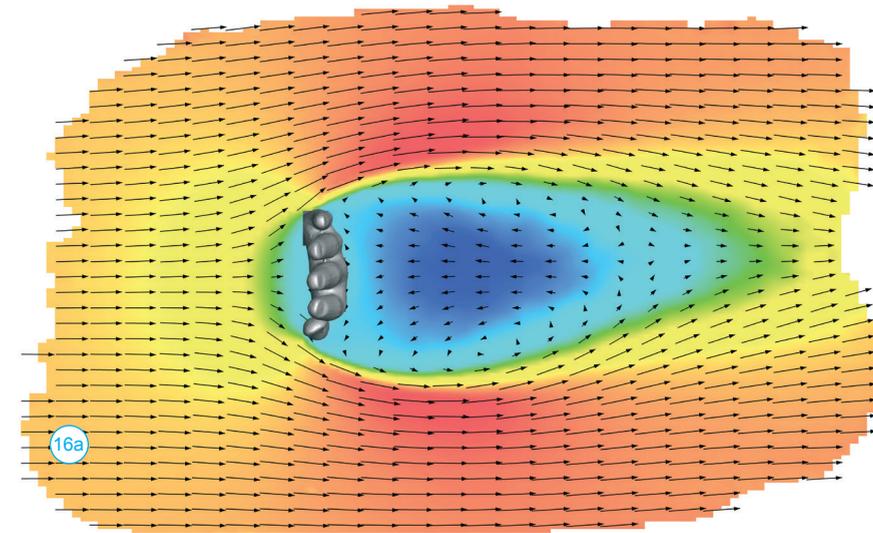
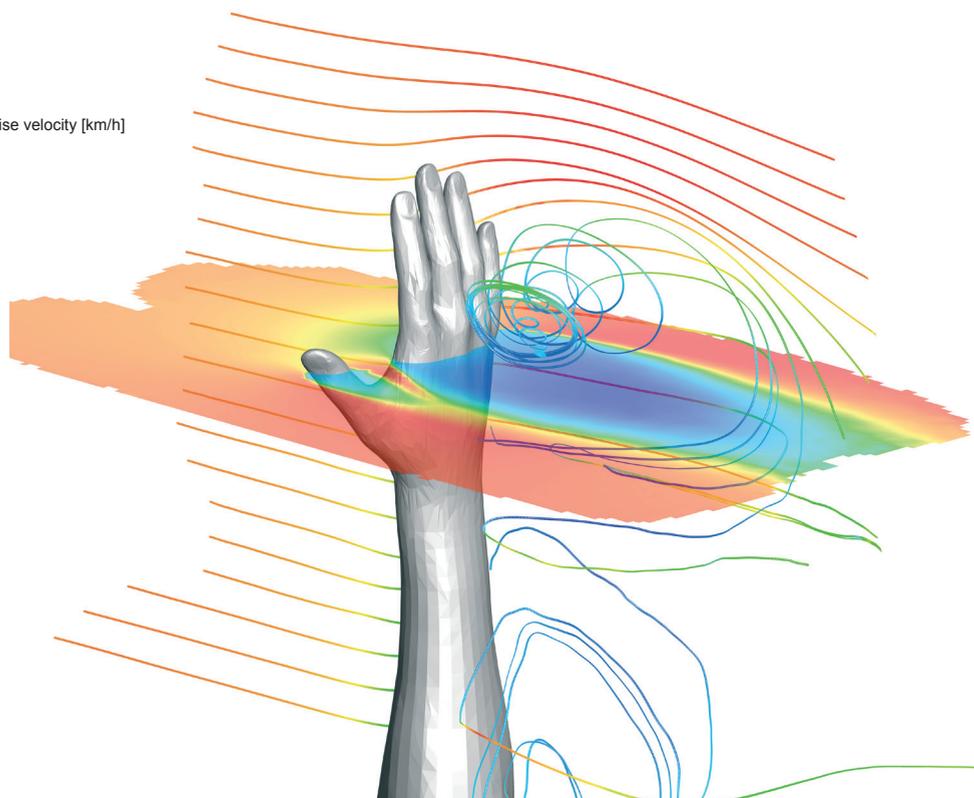


## 15. The flow around a swimmer's hand

The propulsive force of a swimmer depends, among others, on the amount of finger spreading and orientation of a swimmer's hand. The flow around this part of the athlete's body is measured using HFSB in a wind tunnel [7]. Image 15a provides a glimpse of the hand's turbulent wake. The air velocity in the direction of motion of the hand is depicted in figure 15b. In general we can say that the larger the amount of decelerated water and the higher this deceleration (maximum marked dark blue), the higher will be the fluid resistive force, which eventually may help the athlete to swim faster.

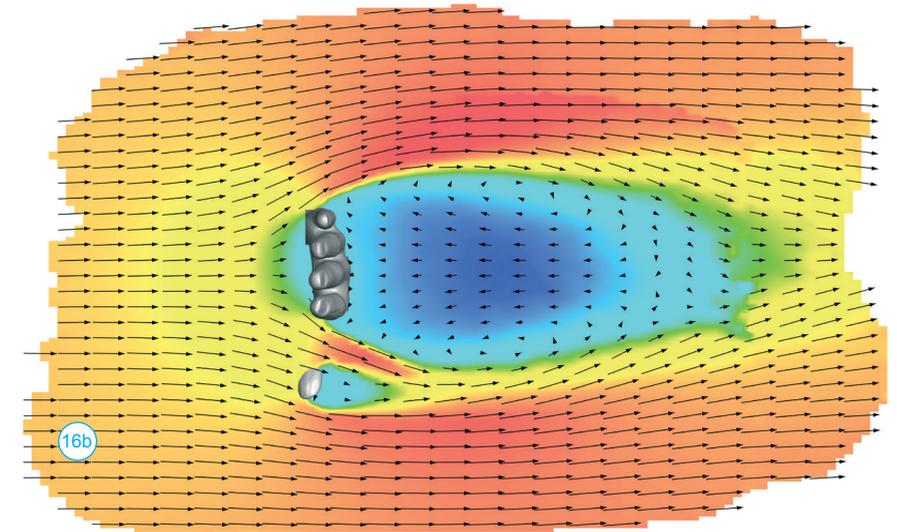
15b

Streamwise velocity [km/h]



16a

Streamwise velocity [km/h]



16b

## 16. The effect of the posture of a swimmer's thumb

The location of the swimmer's thumb, either parallel to the other fingers (16a) or in extended position (16b), makes little difference to the size of the area that contains reverse flow, that is air moving in opposite direction to the airstream further removed from the hand (marked dark blue). This suggests that the hydrodynamic drag of the hand is not much affected either.

# Epilogue

Flows around athletes in different sports have been presented in this brief collection of sports fluid motion. These visualisations, and the various measurement techniques, hopefully demonstrated how we can progress our understanding of sport fluid motion. It also may have sparked ideas to continue to do so in the future, in which way our research keeps having an impact in both elite sports and society in general. We, being the authors of this booklet, certainly aim for this. However, we cannot do this alone and we therefore invite you to contact us to initiate new collaborations in sport aerodynamic research and in sport science in general. Finally, the complexity of the presented flows around the human body is evident. The beauty of these visualisations, however, is possibly as remarkable and for this we want to thank everyone that has contributed to this work. Without your research and your efforts to visualise the fluid motion this booklet would not have been possible.

## Wouter Terra

embedded scientist aerodynamics, TeamNL/TU Delft

## Andrea Sciacchitano

assistant professor aerodynamics, TU Delft

## End Notes

Measurements described by / Figures adapted from:

1. C Jux, A Sciacchitano, JFG Schneiders, F Scarano (2018) Robotic volumetric PIV of a full-scale cyclist. *Exp Fluids* 59:74. <https://doi.org/10.1007/s00348-018-2524-1>. With permission of Springer Nature (CC BY 4.0).
2. C Jux, A Sciacchitano, F Scarano (2020) Flow pressure evaluation on generic surfaces by robotic volumetric PTV. *Meas. Sci. Technol.* 31 104001. <https://doi.org/10.1088/1361-6501/ab8f46>. With permission of IOP Publishing (CC BY 4.0).
3. A Spoelstra, A Sciacchitano, F Scarano, N Mahalingesh (2021) On-site drag analysis of drafting cyclists. *J Wind Eng & Indus Aerodyn* 219 104797. <https://doi.org/10.1016/j.jweia.2021.104797>. With permission of Elsevier (CC BY 4.0).
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5. N Timmer, L Veldhuis (2021) The Impact of Skinsuit Zigzag Tape Turbulators on Speed Skating Performance. *Appl Sci* 11:988. <https://doi.org/10.3390/app11030988>. With permission of MDPI (CC BY 4.0).
6. J van Houwelingen, RPJ Kunnen, W van de Water, APC Holten, GF van Heijst, HJH Clercx (2019) Flow visualisation in swimming practice using small air bubbles. *Sports Eng* 22:13. <https://doi.org/10.1007/s12283-019-0306-5>. With permission of Springer Nature (CC BY 4.0).
7. J van den Berg, R Bazuin, C Jux, A Sciacchitano, J Westerweel, W van de Water (2021) The effect of hand posture on swimming efficiency. *Exp Fluids* 62:245. <https://doi.org/10.1007/s00348-021-03333-1>. With permission of Springer Nature (CC BY 4.0).

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