

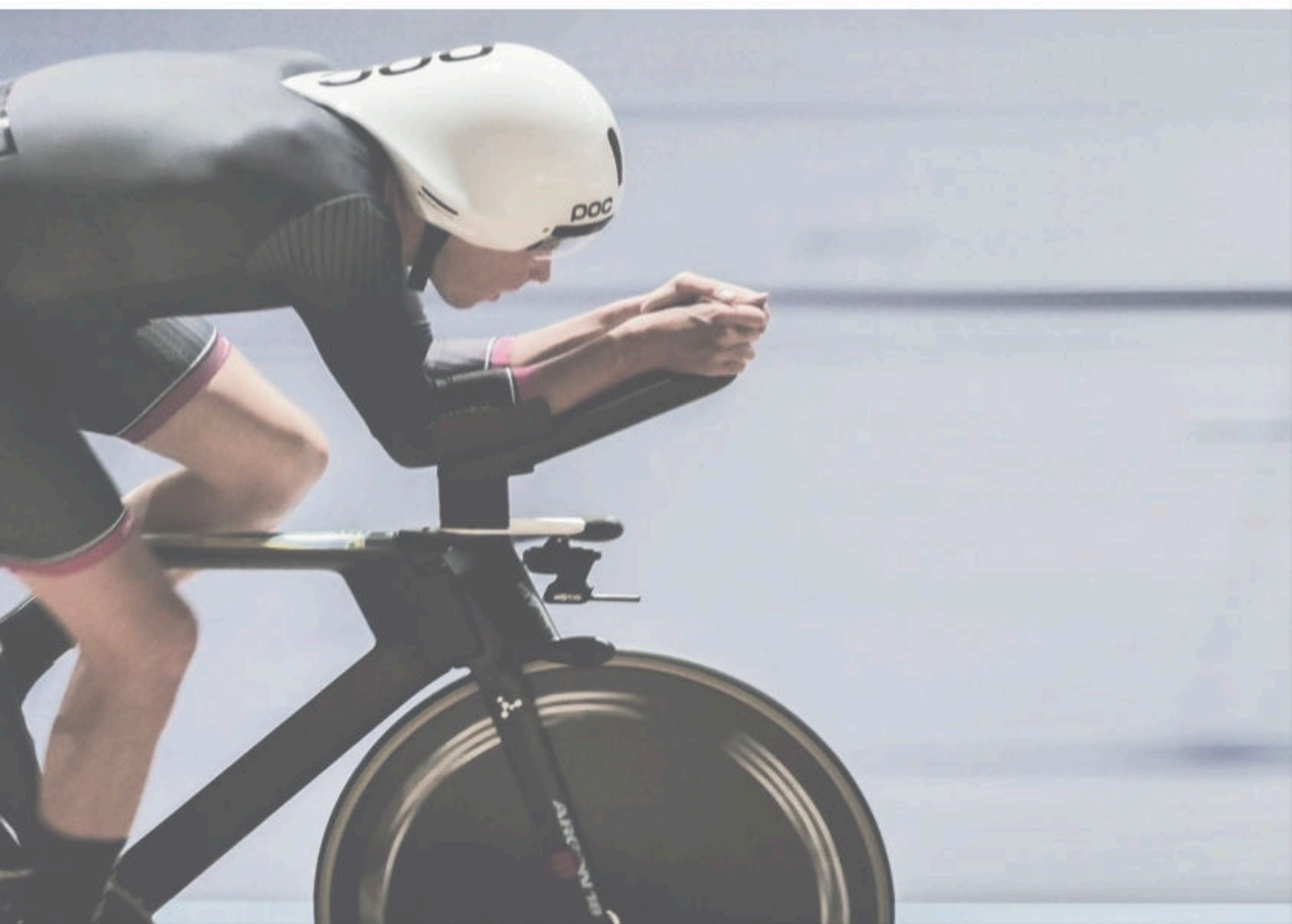


VNIVERSITAT DE VALÈNCIA

Aerosensors in Cycling: Validation of Notio in Indoor, Outdoor, and Wind Tunnel

PhD Thesis

Manuel Ordiñana Pérez





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Aerosensors in Cycling: Validation of Notio in Indoor, Outdoor, and Wind Tunnel

PhD Thesis

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València - May 2025

La doctora Cristina Blasco Lafarga, en calidad de directora, y el doctor Mikel Zabala Díaz en calidad de codirector, de la tesis doctoral presentada por D. Manuel Ordiñana Pérez:

Aerosensors in Cycling: Validation of Notio in Indoor, Outdoor, and Wind Tunnel

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CERTIFICAN:

Que el documento titulado "**Aerosensors in Cycling: Validation of Notio in Indoor, Outdoor, and Wind Tunnel**" se presenta como tesis de compendio a partir de tres artículos realizado por el doctorando Don Manuel Ordiñana Pérez bajo nuestra supervisión. Todos ellos son originales realizados en el periodo del doctorado, y en nuestro criterio reúnen los méritos necesarios para optar al grado de Doctor por la Universidad de Valencia.

Ordiñana-Pérez, M., Mateo-March, M., Monteagudo, P., Zabala, M., & Blasco-Lafarga, C. (2023). Validity of a novel device for indoor analysis of cyclists' drag area. *European Journal of Sport Science*, 23(1), 1-7. <https://doi.org/10.1080/17461391.2021.2012264>

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Y para que así conste a los efectos oportunos, firman la presente certificación en Valencia a 12 de mayo de 2025.

Fdo.: María Cristina Blasco Lafarga

Fdo.: Mikel Zabala Díaz

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CONFLICTS OF INTEREST

The author declares that there is no conflict of interest in his work. He has not received funding and has no direct or indirect links with the instruments used or cited in this research. The development of this doctoral thesis followed the procedures established in the Declaration of Helsinki and was approved by the Ethics Committee of the University of Valencia, Spain (2024383).

INDEX

Acknowledgements	vii
Conflicts of interest	ix
Index	xi
List of publications	xiii
List of abbreviations	xv
List of figures.....	xvii
Abstract.....	xix
Theoretical background	1
General introduction.....	1
External forces.....	2
Aerodynamic force.....	3
Conditioning factors of flow behavior.....	7
Reynolds number	10
Rolling resistance force.....	13
Gravitational force	19
Friction force.....	20
Inertia	22
Origin and evolution of the study of aerodynamics in cycling	25
First power-based mathematical model	26
Wind tunnel.....	27
Towing	29
Coast-down	31
Mathematical models based on power.....	33
Computational fluid dynamics.....	42
Particle image velocimetry	45
Aerosensors.....	51
Rationale for the thesis	63
Aims.....	65
Methodology.....	67
Results	71
Discussion.....	73
Limitations.....	79
Future research	81

INDEX

Conclusions.....	83
Practical applications	85
Spanish summary	87
References.....	101
Publications.....	115
Manuscript 1	117
Manuscript 2	127
Manuscript 3	139

LIST OF PUBLICATIONS

- 1- **Ordiñana-Pérez, M.**, Mateo-March, M., Monteagudo, P., Zabala, M., & Blasco-Lafarga, C. (2023). Validity of a novel device for indoor analysis of cyclists' drag area. *European Journal of Sport Science*, 23(1), 1-7. <https://doi.org/10.1080/17461391.2021.2012264>
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LIST OF ABBREVIATIONS

2D-PIV:	Two-dimensional Particle Image Velocimetry
CCD:	Charge-Coupled Device
CFD:	Computational Fluid Dynamics
CI:	Confidence Interval
CV:	Coefficient of Variation
CV%:	Coefficient of Variation expressed as percentage of SEM
CVV:	Coaxial Volumetric Velocimetry
DFPM:	Direct Force Power Meter
ES:	Effect Size
GPS:	Global Positioning System
HFSB:	Helium-Filled Soap Bubbles
HWA:	Hot Wire Anemometer
ICC:	Intraclass Correlation Coefficient
IC95:	95% Confidence Interval
IMU:	Inertial Measurement Unit
LES:	Large Eddy Simulation
LoA:	Limits of Agreement
LRNM:	Low Reynolds Number Modeling
MD:	Mean Absolute Difference
MSE:	Mean Square Error
NACA:	National Advisory Committee for Aeronautics
OFPM:	Opposing Force Power Meter
PIV:	Particle Image Velocimetry
PIV3C:	Three-dimensional Particle Image Velocimetry
RANS:	Reynolds-Averaged Navier-Stokes equations
RMSE:	Root Mean Square Error
RoF:	Ring of Fire
SEM:	Standard Error of Measurement
SEM95:	Standard Error of Measurement at 95% confidence
SRM:	Schoberer Rad Meßtechnik
SST:	Shear Stress Transport
TAS:	Track Aero System
TEM:	Typical Error of Measurement

LIST OF ABBREVIATIONS

UCI: Union Cycliste Internationale
VE: Virtual Elevation

LIST OF FIGURES

Figure 1. Forces and inertia acting on the cyclist	2
Figure 2. Contributions of pressure and friction drag to total C_D	4
Figure 3. C_D as a function of Re	9
Figure 4. C_D for spheres with different relative roughness	12
Figure 5. Graphical representation of rolling resistance.....	14
Figure 6. Rolling resistance mechanisms and hysteresis factors.....	16
Figure 7. Power required to overcome resistive forces	22
Figure 8. Experimental design of Nonweiler's study.....	28
Figure 9. First prototype of a cycling power meter SRM.....	34
Figure 10. Graphical representation of the VE method.....	40
Figure 11. CFD process	42
Figure 12. Robotic volumetric PIV system	47
Figure 13. RoF experimental design.....	48
Figure 14. Variation field of airflow velocity.....	53
Figure 15. PowerPod	54
Figure 16. Aerosensors	56

ABSTRACT

Aerodynamic resistance is the main limiting factor of performance in cycling at high speed accounting for up to 90% of total resistance above 30 km/h. Optimizing the drag area (C_{DA}) is essential in modern cycling, where victories are often decided by just a few seconds.

Traditionally, C_{DA} has been calculated using wind tunnels, a very expensive method that is inaccessible to many cyclists, or field tests that usually require complex technical processing and may present significant methodological limitations. In this context, Notio emerges as a portable device based on a Pitot-static tube capable of estimating C_{DA} in real time. The aim of this thesis is to evaluate the validity and reliability of Notio compared to other laboratory and field alternatives, as well as to examine its sensitivity to detect small aerodynamic changes both on an indoor track and on the road.

The research is based on three complementary studies that address the following questions. The first focuses on the validity of Notio in the calculation of C_{DA} compared to two validated mathematical models (Virtual Elevation [VE] and Martin) in an indoor velodrome with professional cyclists. The second examines the validity of wind speed calculated by Notio in a wind tunnel compared to a hot-wire anemometer (HWA). The third explores the consistency of C_{DA} calculated by Notio between indoor and outdoor environments, as well as its ability to measure C_{DA} changes produced by different equipment configurations.

The results confirm that Notio shows a high correlation with the reference mathematical models (intraclass correlation coefficient [ICC] > 0.82), although with slightly lower C_{DA} values. The direction of C_{DA} changes for the different positions tested differs between Notio and the mathematical models, which could lead to different recommendations regarding the final position of the cyclist. On the other hand, Notio provides wind speed data with differences of less than 1% compared to an HWA at speeds of up to 50 km/h, maintaining its accuracy even with yaw angles of up to 20°. Additionally, while Martin shows statistically significant differences between indoor and outdoor environments (2.4% higher indoors, $p < 0.001$), Notio offers consistent results regardless of the test environment.

ABSTRACT

However, neither Notio nor Martin demonstrate sufficient sensitivity to reliably detect small aerodynamic changes (less than ± 0.006 - 0.008 m^2), since the standard error of measurement at 95% confidence (SEM95) exceeds the differences observed between different equipment configurations.

In conclusion, this thesis provides scientific evidence on the potential and limitations of aerosensor technology in cycling, laying the groundwork for optimizing the aerodynamic performance of cyclists through portable tools, and offering practical recommendations for their use by coaches, athletes, and sports scientists.

THEORETICAL BACKGROUND

As a cycling coach, during the period I worked with the national team, I experienced the arrival of aerosensors, promising tools that allowed us to conduct aerodynamic assessments integrated into training camps. This innovation represented an opportunity to optimize cyclists' performance outside the laboratory environment. However, we soon observed that the available scientific research was scarce and that the results obtained with these tools were often inconsistent or did not align with the time or power records. This discrepancy between the technological promise and its practical application became the motivation for this research

General Introduction

In fluid mechanics, aerodynamics studies the forces that air exerts on moving bodies. Since aerodynamic drag is the main force opposing forward motion at speeds above 30 km/h and can represent up to 90% of the total resistance produced by the cyclist, this phenomenon is a determining factor for performance (Gibertini et al., 2011). This resistance not only limits speed but also affects energy efficiency and, consequently, overall performance (Capelli et al., 1993).

Aerodynamic optimization has evolved into a fundamental pillar of modern cycling. Research has shown that an optimized position can reduce aerodynamic resistance by up to 16% (Barry et al., 2015). Consequently, biomechanical adjustments are key, as the cyclist's body accounts for 79% of the C_{DA} (Chi et al., 2020). Moreover, both manufacturers and teams invest considerable resources in wind tunnel testing, computational fluid dynamics (CFD) simulations, and field tests to develop and introduce technological improvements based on new models of bicycles and accessories with advanced aerodynamic designs. In competitive cycling, where victory is sometimes decided by just a few seconds, reducing aerodynamic resistance has become a top priority (Malizia & Blocken, 2021).

The systematic analysis of the forces acting on the cyclist and the evolution of methodologies for their measurement constitute fundamental

THEORETICAL BACKGROUND

research fields for performance improvement. Among these forces, aerodynamic resistance stands out due to its relative weight in the power output at competition speeds, which justifies the growing interest in technologies aimed at its analysis. In this context, the validation of devices such as Notio, an aerosensor designed to calculate $C_D A$ in field tests, may represent a significant advance for aerodynamic optimization.

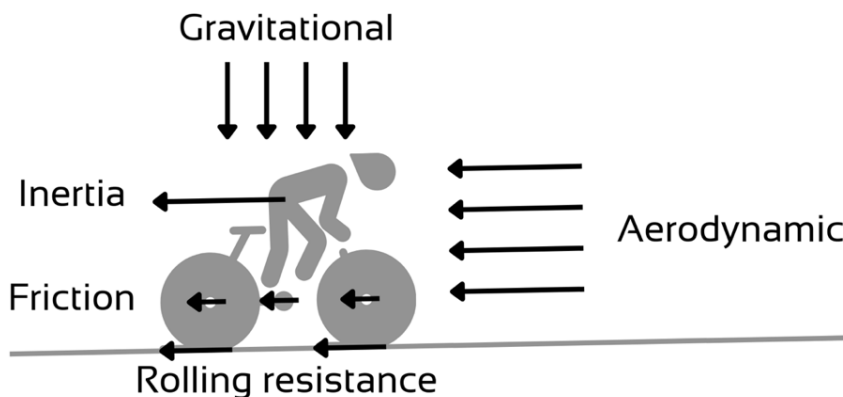
External Forces

Performance in cycling is determined by different physical forces that act simultaneously on the cyclist. Understanding these forces is essential for optimizing performance.

The four main forces that condition the dynamics of cycling motion are aerodynamic force, rolling resistance, gravitational force, and friction (Figure 1). Additionally, inertia, although not a force but a property of matter, is also considered in the analysis of speed variations, as it directly affects the acceleration of the system (Glaskin, 2013).

Figure 1

Schematic representation of the forces and inertia acting on the cyclist during motion



Aerodynamic Force

Aerodynamic force arises from the interaction between the airflow and the cyclist in motion. This force results from the combination of air pressure and tangential stresses acting over the entire surface of the cyclist-bicycle system. The total aerodynamic force can be divided into two main vector components: drag force and lift force (Nørstrud, 2008).

The drag force acts parallel to the free flow. This force opposes the cyclist's forward motion and is mathematically expressed as:

$$F_D = \frac{1}{2} \rho_{\infty} C_D A U^2$$

Where F_D is the drag force (N), ρ_{∞} is the air density in the free flow (kg/m^3), C_D is the drag coefficient (-), A is the reference area (m^2), and U is the relative free flow velocity (m/s).

The lift force acts perpendicular to the drag force, and can be positive (upward), negative (downward), or lateral, depending on the object's geometry and the orientation of the relative free flow. It is mathematically expressed as:

$$F_L = \frac{1}{2} \rho_{\infty} C_L A U^2$$

where F_L is the lift force (N) and C_L is the lift coefficient (-). All other variables are the same as in the previous formula. These two components of aerodynamic force, drag and lift, can be measured through wind tunnel experiments or numerical simulations using CFD (Karna et al., 2014).

To facilitate comparison between different experiments, these forces are often characterized by dimensionless coefficients (C_D and C_L). This allows normalized quantification under equivalent conditions of flow regime, relative geometry, and turbulence, making comparisons between different designs possible (Kensrud & Smith, 2018).

THEORETICAL BACKGROUND

Based on the drag force formula and considering that force is expressed in $\text{kg}\cdot\text{m}/\text{s}^2$, a dimensionless number is obtained by dividing a real force by a reference force with the same units:

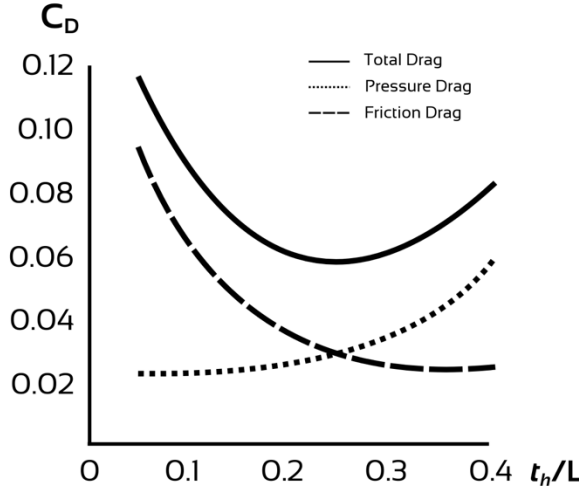
$$C_D = \frac{2F_D}{\rho_\infty U^2 A}$$

In cycling, the product $C_D \times A$ is reported, as accurately estimating the frontal area requires additional methods (Debraux et al., 2011). This approach allows for the direct calculation of aerodynamic force or power without the need to separate two independent variables.

Both the drag and lift components arise from two fundamental physical mechanisms: friction and pressure, which act simultaneously to generate forces (Figure 2), whose magnitude will depend on the flow behavior in each region of the body (King, 2002).

Figure 2

Contributions of pressure and friction drag to total drag coefficient (C_D)



Note. This figure shows the variation of the total drag coefficient (C_D) and its components, pressure drag, and friction drag, as a function of the t_h/L at $Re = 4 \times 10^5$. Where t_h is the body thickness (m), L the length (m) and Re the Reynolds number (-). Figure created from data by Goldstein (1938).

The pressure component acts perpendicularly to the body's surface and arises from static pressure differences generated by the airflow as it interacts with the cyclist. When air hits the front part the flow velocity decreases almost to zero in the area known as the stagnation point. At this point, the air's kinetic energy is converted into static pressure, creating a high-pressure region. Subsequently, the flow is forced to deviate and accelerate around the cyclist's body. Due to the blunt nature of the cyclist-bicycle system, this flow tends to separate from the surface before reaching the rear part, generating a wake characterized by low static pressure that increases resistance (Crouch et al., 2017).

This pressure distribution, high at the front and low at the rear, creates a net force opposite to the direction of motion, known as pressure drag. In cycling, this force represents most of the total drag, with a contribution that can exceed 70% (Forte et al., 2020). The magnitude of this force fundamentally depends on the body's shape and how pressure is distributed along the entire surface. More complex shapes cause early flow separation, increasing the wake and drag, whereas more aerodynamic profiles maintain attached flow for longer, reducing these pressure losses.

From an energetic perspective, this process can be described as a conversion between static pressure and flow velocity. The air that stops when hitting the cyclist transforms its kinetic energy into pressure, while at the rear, turbulent and detached air generates dissipation losses (Batchelor, 2000).

Pressures in the flow are locally quantified through the pressure coefficient C_p (-), defined as the difference between the local pressure p (Pa) and the free flow pressure p_∞ (Pa), normalized by the free q_∞ (Pa):

$$C_p = \frac{p - p_\infty}{q_\infty}$$

THEORETICAL BACKGROUND

According to the no-slip condition, the air in direct contact with the body surface has zero velocity. As we move away from that surface, flow velocity gradually increases until it reaches the free flow velocity. This velocity gradient, present in a thin region near the surface called the boundary layer, generates shear stress on the body. The sum of these tangential stresses produces the friction drag force (Anderson, 2010). This tangential stress at the surface is also known as wall shear stress and can be expressed using Newton's law of friction for fluids:

$$\tau_w = \eta \left(\frac{\partial v_x}{\partial y} \right)_{\text{wall}}$$

where τ_w is the wall shear stress (Pa), η is the fluid viscosity (Pa·s), and $\left(\frac{\partial v_x}{\partial y} \right)_{\text{wall}}$ is the velocity gradient at the wall evaluated right at the surface (Newton et al., 1999).

The magnitude of this friction directly depends on the state of the flow in the boundary layer. In laminar flow, the gradient is smoother, and thus the shear stress is lower. In contrast, when the boundary layer becomes turbulent, the mixing of fluid layers increases the momentum exchange, which raises the gradient at the wall and therefore the friction.

The magnitude of this friction can be expressed in a dimensionless form using the friction coefficient C_f (-), defined as the relationship between the wall shear stress τ_w (Pa) and the dynamic pressure of the free flow q_∞ (Pa)

$$C_f = \frac{\tau_w}{q_\infty}$$

Although in cycling friction usually represents a smaller part of the total drag compared to pressure, since pressure drag predominates in bluff bodies like the cyclist-bicycle assembly (White, 2010), its relevance is greater in areas where the flow remains attached, such as the front part of the helmet, the arms, or the upper part of the trunk. This factor is determinant for equipment design, since the microscopic roughness of materials directly affects the state of the boundary layer and, therefore, the total friction (Brownlie et al., 2009). Therefore, a balance is sought between keeping the flow attached to the surface but without excessively increasing friction. This principle is used strategically through the use of rough or textured surfaces

placed in areas where the flow tends to separate. When induce an early transition of the flow from laminar to turbulent, flow separation is delayed, reducing pressure drag at the cost of a slight increase in friction drag. This technique is implemented through technical fabrics, patterns, or surface treatments (Brownlie et al., 2009).

Conditioning Factors of Flow Behavior

The interaction of the air with the surface of the cyclist and the bicycle depends on several factors that modify the magnitude such as the distribution of friction and pressure stresses.

The relative velocity between the cyclist and the air affects both the magnitude of the forces and the nature of the flow regime. At moderate speeds, several areas of the cyclist-bicycle system exhibit laminar flow, increasing the importance of viscous friction. However, at competition speeds, the Reynolds number increases promoting the transition to turbulent flow in more regions of the body and bicycle. This change in the flow regime alters the balance between friction drag and pressure drag, and the location of the flow separation point, modifying the shape and size of the wake. Wind tunnel studies have confirmed that the C_D varies significantly with the Reynolds number, decreasing by up to 20% in the speed range from 20 to 70 km/h. This demonstrates aerodynamic sensitivity to velocity (Taylor et al., 2024).

Atmospheric conditions alter the physical properties of air, particularly density (ρ) and dynamic viscosity (μ), influencing the flow behavior around the cyclist. Air density is directly influenced by these three factors. Air molecules have greater kinetic energy and are more likely to separate as the temperature rises which lowers density. Density increases as a result of molecules being more compressed at lower temperatures. In contrast to lower pressure which permits air to expand higher barometric pressure compresses the air increasing its density. Density is impacted by relative humidity as well. Compared to the primary constituents of dry air such as nitrogen and oxygen water vapor has a lower molecular mass. Thus, the average molecular mass falls as the amount of water vapor in the air rises and as a result the air density also falls.

THEORETICAL BACKGROUND

Lower density reduces the flow's dynamic pressure (q), which determines both the magnitude of the pressure at the front area of the body, where the flow stagnates, and the suction at the rear area, where the wake forms. As density decreases, both pressures are reduced, diminishing the difference between them and thus reducing pressure drag.

On the other hand, the air's dynamic viscosity expresses its resistance to internal deformation. Although its value is considered practically constant under typical atmospheric conditions, viscosity increases with temperature. This increase is due to the rise in the gas molecules' kinetic energy, intensifying the momentum exchange between flow layers. Applying the empirical relationship proposed by Gottlieb (1979), it is estimated that between 15 °C and 40 °C, air viscosity can increase by approximately 7%. However, since density decreases to a greater extent, the total mass of air interacting with the cyclist's surface is lower, implying that, even with higher viscosity, the total tangential stresses decrease.

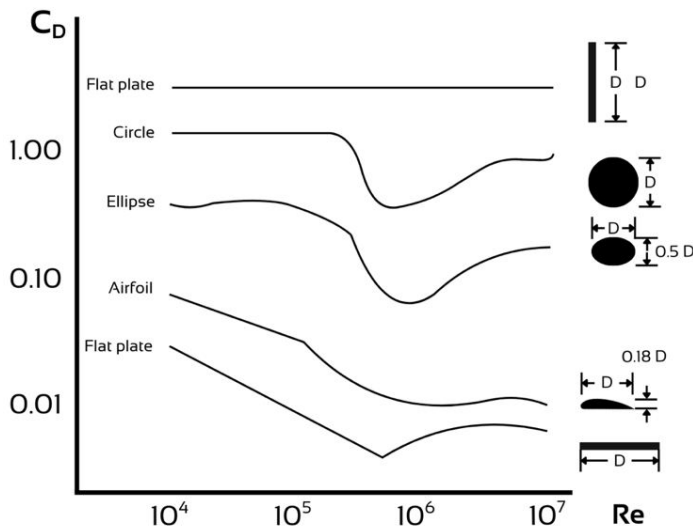
The interaction between air density and viscosity directly affects boundary layer behavior. When density decreases, as occurs mainly under hot conditions or low atmospheric pressure, the mass of air in contact with the surface also reduces. This implies less kinetic energy in the boundary layer, limiting its ability to remain attached to the surface under adverse pressure gradients. Consequently, the flow becomes more prone to early separation, expanding the rear wake, increasing the low-pressure region behind the cyclist, and potentially raising pressure drag. This behavior is commonly associated with low-inertia, high-dissipation flows, conditions reflected by a low Reynolds number. In general, a boundary layer with less energy tends to separate earlier, generating greater rear suction. Nevertheless, in most practical situations, the beneficial effect of reduced density on total resistance outweighs the potential increase in pressure drag due to earlier flow separation.

Another relevant parameter is body size, which can be characterized in several complementary ways, such as characteristic length, frontal area, or geometric shape. The characteristic length is defined as the primary dimension in the flow direction. A greater length means that air particles remain in contact with the surface for longer as they move along, causing further boundary layer development. As this layer grows, internal flow

disturbances amplify and may become unstable, promoting the transition from laminar to turbulent flow. This phenomenon is reflected in Re (Figure 3), where the system's characteristic length appears as a direct parameter in its calculation. Meanwhile, the frontal area determines the surface exposed perpendicularly to the airflow, increasing the amount of air that must be displaced for the cyclist to move forward. This physical mechanism generates higher pressure at the body's front (stagnation point), increasing pressure drag forces. Additionally, the cyclist-bicycle system's geometric shape determines how the flow adheres to and separates from the surface. Blunt bodies cause early separations and wide wakes, whereas aerodynamic profiles, such as those based on NACA geometries, guide the flow more effectively, reducing low-pressure zones.

Figure 3

Drag coefficient (C_D) of bluff bodies and aerodynamic bodies as a function of Reynolds number (Re)



Note. Body shapes shown on the right are scaled by characteristic diameter (D). Adapted from Munson et al. (1998).

In addition to the general shape of the system, interference zones that occur in transitions between different parts of the body and components must be considered, such as between the thighs and the down tube, the

helmet and the back, or the arms and the handlebar. These areas generate complex interactions between flows, where vortices, local separations, and pressure fluctuations can form. Although their impact is localized, they can contribute significantly to total drag. Aerodynamic optimization seeks to minimize these effects through a fluid transition between surfaces and an optimized integration of all elements (Di Meo et al., 2024).

The surface roughness of the components is also an important factor. As we have commented, although it can increase friction, its effect can also be beneficial if applied in a controlled manner. By inducing an early transition to turbulent flow in areas prone to separation, it is possible to delay it, reducing pressure drag (Brown et al., 2023).

Finally, proximity to the ground, known as ground effect, can modify flow behavior in the lower part. The interaction with a nearby solid surface such as asphalt generates an acceleration channel between the body and the ground, altering the pressure distribution. Yi et al. (2020) showed that the incoming airflow generates an increase in the rotational resistance of a disc wheel in conditions of proximity to the ground. Meanwhile, Malizia and Blocken (2020) demonstrated that including the ground in CFD simulations of a wheel with spokes reduces the drag coefficient by up to 1.8% and modifies the pressure distribution in the lower section of the wheel, confirming that the ground influences the flow behavior in that region.

Reynolds Number

One of the most important factors in the study of cycling aerodynamics is the Reynolds number (Re) which makes it possible to predict how the flow will behave around the body based on its regime (laminar, transitional or turbulent). This dimensionless quantity which is represented by the following formula connects the inertial forces to the viscous forces in the flow.

$$Re = \frac{\rho_{\infty} UL}{\mu}$$

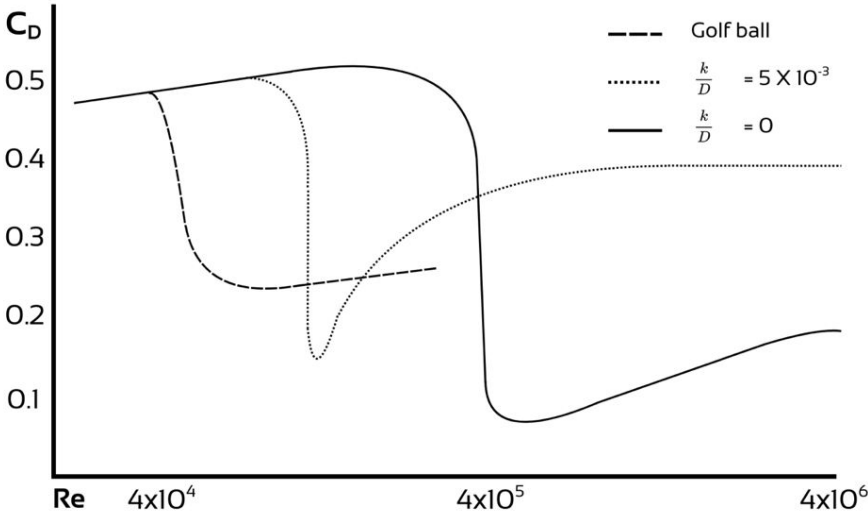
where ρ_{∞} is the free-stream air density (kg/m^3), U is the flow velocity (m/s), L is a characteristic length of the body (m), and μ is the dynamic viscosity of air ($\text{kg/m}\cdot\text{s}$) (Reynolds, 1895).

Re varies from about 2×10^5 to more than 2×10^6 in competitive cycling depending on the body part speed and geometry examined (Forte et al., 2020). For instance, values of $Re \approx 5 \times 10^5$ are obtained at a typical speed of 11 m/s (≈ 40 km/h) for a characteristic length like the cyclist's torso ($L \approx 0.7$ m) (Terra et al. 2020). The lower limbs show usually values between 2×10^5 and 2×10^7 the upper limbs range from 1×10^5 to 3×10^5 and the helmet falls between 1×10^5 and 2×10^5 contingent on geometry and flow orientation (Terra et al., 2020; Forte et al., 2020).

This variability in Re is especially relevant due to the phenomenon known as drag crisis, which occurs when the flow around the body transitions from laminar to a turbulent regime. In this process, the C_D experiences a significant drop as a result of the boundary layer transition to turbulence, allowing the flow to remain attached for longer and reducing the wake (Figure 4). In blunt bodies such as the cyclist with the bicycle, this phenomenon can have a considerable impact on total aerodynamic resistance.

Figure 4

Drag coefficient (C_D) as a function of Reynolds number (Re) for spheres with different levels of relative roughness (k / D)



Note. k is the equivalent roughness height (m) and D is the diameter of the sphere (m). Adapted from Munson et al. (1998).

Forte et al. (2020) found that the drag crisis manifests between 3 m/s to 9 m/s or 3.2×10^5 and 9.6×10^5 in terms of Re . The critical velocity at which this transition takes place can differ greatly for individual body segments such as the arms or legs. For instance, the critical velocity may be as much as 25 m/s on the lower portion of the extended leg and the upper portion of the arm while it may be as low as 10 m/s on the upper thigh (Terra et al., 2020). This spatial distribution of the critical Re highlights the importance of considering each body segment separately when analyzing or designing aerodynamic solutions.

The relevance of Re is not limited to flow characterization; it also has practical applications in equipment optimization. For example, using fabrics with surface roughness can induce an early transition to turbulence, shifting the drag crisis to lower velocities and reducing aerodynamic resistance. This strategy is particularly useful in segments where the critical velocity exceeds

race speed, such as the arms or the lower legs (Brownlie et al., 2009; Terra et al., 2020).

Additionally, knowing Re is essential to ensure conditions of dynamic similarity between experimental tests, a key aspect in aerodynamic analysis and the validity of its extrapolation to real conditions.

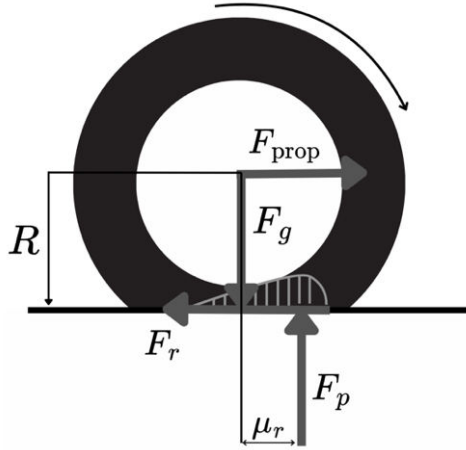
Rolling Resistance Force

During the cyclist's movement, a part of the total energy developed is lost mainly due to deformations that occur in the tires. This energy loss, called rolling resistance, acts in opposition to movement. Unlike aerodynamic resistance, whose magnitude grows with the square of velocity, rolling resistance is considered practically constant with velocity in simplified models (although there is a slight dependency), and is determined mainly by mechanical and structural properties of the tire, the terrain, and the interaction between both. Rolling resistance is the second most relevant resistive force on flat terrain, representing approximately 10% of the total resistance at competition speeds (Grappe et al., 1997).

The origin of rolling resistance is found in the deformations experienced by the tire and the surface in the contact zone, which is not a point but a small extension. In this region, the normal pressure is not uniformly distributed but tends to concentrate more in the front part of the contact patch, which displaces forward the effective application point of the ground reaction force with respect to the wheel axis. This asymmetry generates a resistive torque that must be compensated by a horizontal force F_r (N) to maintain the bicycle's forward motion (Figure 5).

Figure 5

Schematic representation of the rolling resistance model showing the main force components



Note. The diagram includes the rolling resistance force (F_r), normal force (F_p), gravitational force (F_g), propulsive force (F_{prop}), and wheel radius (R). The shaded area under the wheel represents the contact patch between the tire and the ground. μ_r defines the offset between the wheel axis and the effective point of force application, which generates a resistive torque.

This model can be defined as:

$$F_r = \mu_r \cdot \frac{F_p}{R}$$

where μ_r is the rolling friction coefficient that represents the distance between the wheel axis and the application point of the vertical ground reaction force (m), F_p is the normal force (N) (which equals the total weight on flat terrain), and R is the wheel radius (m) (Müller and Hofmann, 2008).

This approach allows direct measurement of μ_r in laboratory through a traction experiment in which the horizontal force necessary to maintain movement is recorded. Knowing the wheel radius and the system weight, μ_r can be derived using:

$$\mu_r = \frac{F_r \cdot R}{F_p}$$

In this case, the rolling resistance coefficient C_{rr} (-) which is the dimensionless expression used in cyclist dynamics models and is interpreted as a measure of rolling efficiency, can be calculated through the relationship with μ_r in:

$$C_{rr} = \frac{\mu_r}{R}$$

The classic formulation is expressed as:

$$F_r = C_{rr} \cdot N = C_{rr} \cdot m \cdot g \cdot \cos(\alpha)$$

where N is the force normal to the plane (N) (which is reduced according to the inclination angle α), m is the total cyclist-bicycle mass (kg), and g (m/s²) is the gravitational acceleration.

On the other hand, the drum test is the most precise experimental method to determine the rolling force (Hall & Moreland, 2001). In this test, the tire is pressed against a rotating drum while measuring the torque T (N·m) needed to maintain a constant speed. Knowing the drum radius r_{drum} (m), the rolling resistance force F_R (N) can be calculated as:

$$F_R = \frac{T}{r_{\text{drum}}}$$

The result is adjusted with speed to recognize its dependence and is also corrected to undo the effect of the drum curvature. In this case, from F_R and perpendicular force Z (N), the C_{rr} is calculated:

$$C_{rr} = \frac{F_R}{Z}$$

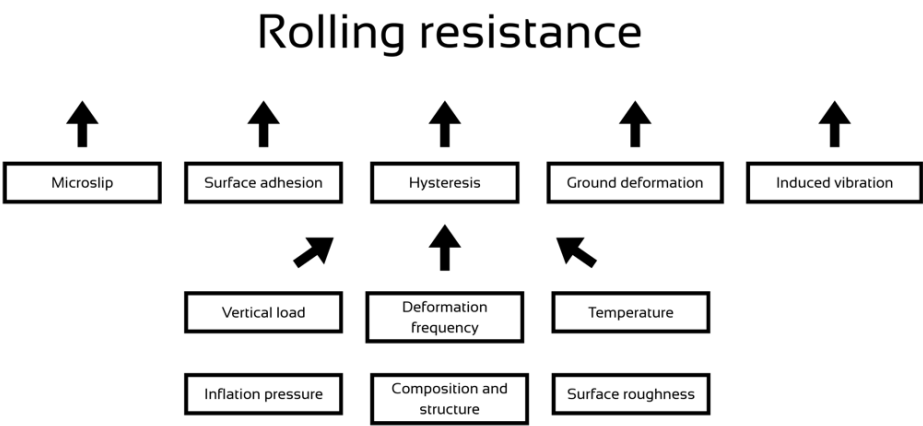
Just as with the C_D , the C_{rr} allows for describing rolling efficiency independently of physical parameters, such as total mass, wheel radius, or terrain inclination. Consequently, its use facilitates comparison between

THEORETICAL BACKGROUND

different experimental conditions without the need to specify all values in each case.

The magnitude of rolling resistance, and therefore of C_{rr} , is conditioned by several physical mechanisms (Figure 6). On firm and regular surfaces, the main responsible for this resistance is tire hysteresis, that is, the energy loss that occurs when the material deforms under load and does not completely recover its original shape when unloaded. This cyclic deformation generates an internal energy dissipation in the form of heat, which repeats with each wheel revolution. The intensity of this phenomenon depends on several factors.

Figure 6
Schematic representation of the main mechanisms that cause rolling resistance and the factors that condition the magnitude of hysteresis



Inflation pressure is a determining factor. Lower pressures increase the contact surface and the volume of deformed material, which increases losses due to hysteresis as demonstrated by the study of Lim et al. (2011), where it was observed that rolling resistance was significantly higher at 60 psi (5.6 ± 0.7 N) compared to 120 psi (4.2 ± 0.8 N) (Lim et al., 2011).

Vertical load is associated with the total weight of the cyclist and the bicycle, also directly affects the degree of tire deformation, the greater the load, the deeper the contact patch and the higher the energy dissipation. This

effect increases in dynamic situations, for example, on velodrome curves, where, due to centrifugal acceleration, cyclists may experience forces of up to twice gravity. This phenomenon doubles the rolling resistance and explains the deceleration cyclists experience on curves (Kyle, 2003).

Tire compound stiffness, determined by the rubber composition and internal structure, influences the material's ability to recover its shape. Tires with softer compounds tend to experience greater deformation during rolling, which increases hysteresis losses and, consequently, rolling resistance (Zhang et al., 2016).

Temperature also modifies the viscoelastic properties of the material. At higher temperatures, some compounds behave more elastically, which may reduce internal energy dissipation, although this effect depends on the thermal range and rubber type. Each compound has an optimal working temperature related to hysteresis (Clark & Loo, 1976).

Deformation frequency, directly related to rolling speed, also influences hysteresis behavior. At higher speeds, the frequency with which the material deforms and recovers increases, which can modify the behavior of the rubber and, consequently, the rolling resistance. This effect is generally small in the normal range of usual speeds in cyclists, so in practical applications C_{rr} can be considered independent of speed (Grappe et al., 1997).

Even on surfaces considered firm, terrain roughness can generate additional micro-deformations in the tire that increase hysteresis. Tires deform to adapt to small surface irregularities. A smoother pavement causes less tire distortion, while rolling resistance can double on rough pavements (Kyle, 1988a).

In addition to hysteresis, another mechanism contributing to rolling resistance is surface adhesion between the tire and the ground. This phenomenon results from intermolecular Van der Waals forces acting at the real micro-contact areas between the rubber and the surface, creating a temporary attraction between them. At the molecular level, the rubber momentarily adheres to the ground, and this bond must be broken during wheel rotation, which requires energy. Although its magnitude is smaller than that of hysteresis, adhesion can have a significant impact under certain conditions, especially on very smooth surfaces where the real contact area increases (Persson, 2001).

THEORETICAL BACKGROUND

Oh et al. (2019), in a study on rubber compounds for tires, estimated that in dry conditions, adhesion friction can represent around 15% of the total rolling resistance, while its contribution on wet surfaces is practically nil. This friction is conditioned by factors such as rubber composition, ground texture, applied load, contact time, and separation speed. Tires with more adherent compounds tend to have greater traction, but can also increase energy losses due to adhesion, which poses the compromise between grip and rolling efficiency.

Induced vibration is another additional mechanism of energy loss that can influence rolling resistance, especially on rough or irregular surfaces. When the wheel runs on this type of terrain, irregularities cause vertical oscillations in the cyclist and the bicycle. These oscillations are not perfectly elastic and cause energy losses through different mechanisms. Part of the energy is dissipated in the tire due to the rapid and repeated deformations of the rubber, and another part is lost by the vertical movement of the cyclist's body and the bicycle, which absorb energy through the contact points, as well as by internal bending and frictions of the material. In this sense, Hölzel et al. (2012) recorded increasing values of vertical acceleration under the saddle with increasing terrain roughness, with average values of 0.05 m/s^2 on asphalt and up to 0.57 m/s^2 on cobblestones, in addition to observing a clear linear relationship with speed. Other studies also observed that the magnitude of vibrations increased with speed and was greater on surfaces with a higher coefficient of rolling resistance, which confirms the relationship between induced vibrations and energy loss during rolling (Meyer et al., 2016).

Microslip is another variable that also contributes to rolling resistance. This occurs inside the contact patch, where some regions of the tire experience relative displacements with respect to the ground, without producing a total slip. These small differences in speed in different areas of the tire cause shear stresses, which when accumulated, generate a force of resistance to movement. The energy dissipated by this mechanism accumulates in each revolution of the tire that constitutes an inherent loss to contact, even in rolling conditions without traction (Pauwelussen, 2015).

A factor related to microslip is the steering angle of the wheel with respect to the trajectory. In recordings made in a 250-meter velodrome, it

was observed that even on straightaways, due to the banking of the track, it was necessary to maintain an average steering angle of approximately 1° to maintain a straight trajectory. This angle increased up to 4° in curves, while during normal pedaling, the angle naturally oscillated between -4° and $+8^\circ$ with each pedal stroke (Kyle, 2003). A steering angle of only 2.5° can increase the coefficient of rolling resistance by approximately 15%, with a non-linear relationship in which greater angles produce greater increases (Moore 1987).

Finally, on soft surfaces, such as loose soil or sand, a part of the rolling resistance is also due to ground deformation. Under these conditions not only the tire deforms, but also the ground under the wheel, which implies additional mechanical work. Unlike hysteresis, where energy is dissipated within the tire, here the loss occurs in the terrain, which absorbs energy in a non-recoverable way. This type of resistance can be very high depending on soil consistency, contact volume, and inflation pressure. In studies with mountain bikers, it has been observed that the coefficient of rolling resistance can triple in sand or grass compared to asphalt, potentially representing up to 65% of the total resistance under some conditions (Bertucci et al., 2013).

Gravitational Force

The gravitational force is the component of the weight of the cyclist and bicycle assembly that acts parallel to the inclined plane of movement. Unlike aerodynamic resistance or rolling resistance, which is conditioned by various physical and mechanical factors, gravitational force depends solely on weight and terrain slope. Its magnitude is proportional to the product of the total mass and the gravitational acceleration projected along the direction of displacement.

This force can behave as resistive or favorable depending on the direction of the slope. On an ascent, the weight component acts against movement, which forces the cyclist to develop greater effort to maintain speed. On a descent, the same component acts in the direction of displacement, which generates an acceleration of the system, reducing the power necessary to move (Fonda & Šarabon, 2012).

THEORETICAL BACKGROUND

The gravitational force is described as:

$$F_g = m \cdot g \cdot \sin(\alpha)$$

where F_g is the gravitational force (N), m is the total mass (kg), g is the gravitational acceleration (m/s^2) and α is the angle of inclination of the terrain with respect to the horizontal (*rad*).

Unlike other forces such as aerodynamic, which depend on the square of velocity, or rolling resistance, which depends fundamentally on material deformation, gravitational force maintains a linear relationship with mass. This explains the impact that weight reduction has on a cyclist's performance, especially in mountain stages where up to 90% of the total power developed can be allocated to overcome the climbs (Wolf & Saupe, 2017).

Friction Force

Friction force is a tangential interaction between two surfaces in contact, provided there is a normal force holding them together. In cycling this force is necessary to transfer the cyclist's mechanical movements to the ground allowing for stable cornering, braking and propulsion (Glaskin, 2013).

From a physical perspective there are two types of friction, kinetic friction and static friction. From a physical perspective there are two types of friction: kinetic friction and static friction. When there is no relative sliding between the contact surfaces static friction keeps the tire stuck to the ground preventing skidding and facilitating the transfer of pedaling force braking and cornering. In this instance friction functions as a reaction force that does not produce work because there is no displacement in the forces direction which prevents energy from dissipating.

In contrast, kinetic friction arises when the tire loses grip and slides over the ground, as happens during skidding. In this case, relative displacement between the surfaces exists, and friction generates resistance to movement that dissipates energy. Kinetic friction also appears in other areas, such as in drivetrain mechanisms, where contact between moving components produces constant energy losses that affect pedaling efficiency (Lorenz & Persson, 2012).

Coulomb's law describes the magnitude of the friction force, which states that this force is proportional to the normal force acting on the contact surface:

$$F_f = \mu \cdot N$$

Where F_f is the friction force (N), μ is the coefficient of friction (-), and N is the normal force (N) (Popova & Popov, 2021). The coefficient of friction varies depending on tire characteristics, surface conditions, the presence of contaminants (such as water and dust), and temperature (Ezzat et al., 2014). Furthermore, a distinction is made between the static friction coefficient μ_s and the kinetic friction coefficient μ_k , with $\mu_s > \mu_k$ in most cases. This difference explains why a wheel that begins to slide tends to lose grip quickly and becomes harder to control (Huang, 2020).

In cycling static friction allows maintain traction without associated energy losses. It is crucial for exerting force on the ground without skidding particularly when braking cornering or accelerating. On the other hand, critical circumstances like skidding where efficiency and control are lost, and increased tire wear are linked to the emergence of kinetic friction.

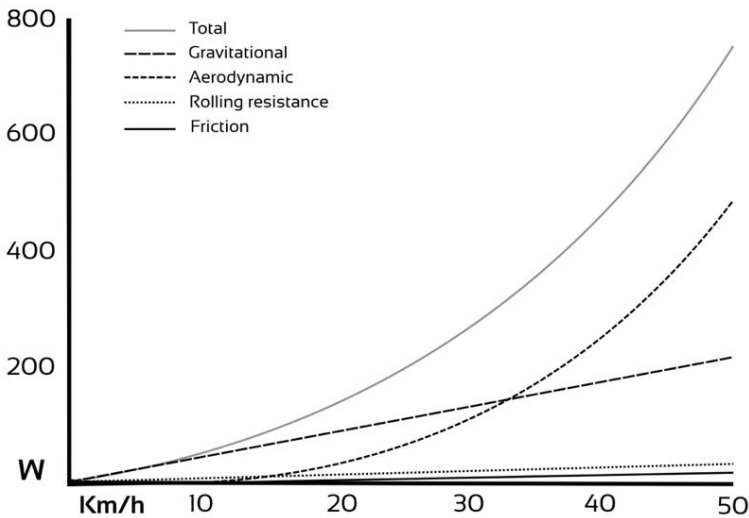
It is worth noting that cyclists in disciplines such as mountain biking may make strategic use of kinetic friction. In these modalities, controlled sliding is part of the technique, especially when cornering on loose or slippery terrain. Although this practice involves energy loss, it may be necessary to maintain balance or the optimal trajectory (Lopes & McCormack, 2017).

Friction also appears in the drivetrain mechanisms of the bicycle. In this case, it is kinetic friction generated at the contact points between the chain, chainrings, sprockets, and bearings. This friction causes mechanical losses, reducing the useful power transmitted to the rear wheel. Under optimal conditions, these losses account for 2.3% of the total power developed (Martin, 1998), although they can increase if the drivetrain is not in proper condition.

The contribution of these resistive forces to the cyclist's energy balance varies according to speed. At high speeds, aerodynamic resistance becomes the predominant factor, whereas at lower speeds, frictional forces, whether associated with rolling resistance or mechanical losses, exert a greater influence (Figure 7).

Figure 7

Graphical representation of the power required to overcome the different resistive forces as a function of speed



Note. Based on the model by Martin et al. (2006b), the figure represents the power required for a cyclist with a total mass of 80 kg, a drag area ($C_D A$) = 0.3, a coefficient of rolling resistance (C_{rr}) = 0.003, air density = 1.2 kg/m³, terrain slope 2%, and a transmission efficiency 97.7%.

Inertia

Inertia is a fundamental property of matter that describes its tendency to maintain its state of rest or uniform rectilinear motion, unless acted upon by an external force that was described by Newton as an inherent force of matter, refers to the ability of a body to persist in its state (McLaughlin, 2008). In the context of cycling, this property manifests as an effective resistance to changes in speed, both during acceleration and deceleration, acting as a transient component within the dynamic balance.

From the perspective of Newton's second law, inertia translates into the need to apply a net force to modify the system's state of motion. Although it is not strictly a force, its effect can be modeled through an effective inertial force that must be overcome during acceleration or compensated during deceleration. It is expressed as:

$$F_i = m \cdot a$$

where F_i represents the inertial force (N), m is mass (kg), and a is longitudinal acceleration (m/s^2). This force only appears when there is a change in speed, and its magnitude is proportional to the product of mass and the desired acceleration (Wittman, 2018).

During a speed change, the cyclist must generate additional power to overcome inertia. This power, called acceleration power, can be expressed as:

$$P_{acc} = F \cdot v = m \cdot a \cdot v$$

where P_{acc} is the instantaneous power required to accelerate (W), v is the system's speed at that moment (m/s), and a is the applied acceleration (m/s^2). This expression shows that the energy cost of an acceleration depends not only on the rate of speed increase but also on the speed at which the acceleration occurs.

The velocity gain associated with this process implies an accumulation of kinetic energy E_k (J) proportional to the mass and the square of the speed reached (Martin et al., 1997):

$$E_k = \frac{1}{2}mv^2$$

In addition to the total mass of the system, the rotational moment of inertia of the wheels and other rotating components of the bicycle, such as chainrings, cranks, or sprockets, are other factors that also contribute to inertia in cycling. These elements rotate as the cyclist moves, and their acceleration requires a fraction of the power developed.

THEORETICAL BACKGROUND

This rotational contribution can be incorporated through the concept of effective mass, which includes the energetic equivalent of the rotation of these components:

$$m_{ef} = m + \sum \left(\frac{I}{r^2} \right)$$

where m_{ef} is the system's effective mass (kg), I is the moment of inertia of each component ($\text{kg} \cdot \text{m}^2$), and r is its radius of rotation (m). This effect is relevant in the wheels, since a significant part of their weight is distributed on the outer edge, considerably increasing their moment of inertia. Martin et al. (1998) reported that the approximate moment of inertia of two road bike wheels is $0.14 \text{ kg} \cdot \text{m}^2$.

Under constant speed conditions, inertia does not contribute to the force balance, as there is no acceleration. However, its influence can be decisive during intermittent efforts such as sprints. A cyclist's ability to overcome this transient resistance depends on their maximum power output, body mass, and the material characteristics used (van Ingen Schenau et al., 1994). Steinhardt (2016) demonstrated that, for an average power of 200 W, the fraction of power allocated to overcoming inertia can be significant during accelerations at low speeds. However, due to its transient effect, the contribution to the total energy balance over the course of a stage is small. In an analysis applied to Tour de France data, the energy associated with inertia represented less than 5% of the total (Steinhardt, 2016).

Origin and evolution of the study of aerodynamics in cycling

The research on aerodynamics in cycling emerged from the need to understand how to reduce aerodynamic resistance, an increasingly relevant factor as the speeds achieved increased. Malizia and Blocken (2020) point out that the recognition of aerodynamic resistance as a critical element occurred at the end of the 19th century, a period in which it was identified as the main resistive force. Aerodynamic optimization strategies have evolved as a result of the development of conceptual foundations, mathematical formulations, and experimental protocols, driven by technological advances and competitive rivalry.

Advances in science and technology, the historical evolution of the bicycle, and the rise of competitions, have all been connected to the development of aerodynamic research in cycling. Karl von Drais created the first prototype for a bicycle in 1817 with the “Laufmaschine” a basic model initially intended for transportation. The pedal propulsion system (Lallement, 1866), tensioned spokes (Hadland & Lessing, 2014) the safety bike (Sharp, 1896) and the pneumatic tire (Wilson, 2004) were some of the technological advancements that changed this original design. These advances made it easier to reach higher speeds, which led to the need to research the reduction of aerodynamic drag. The world hour record, officially recorded for the first time by Frank Dodds on March 25, 1876 (Heijmans & Mallon, 2011), became a reference for evaluating aerodynamic improvements. Eliminating factors such as wind and slope provided a regulated environment where aerodynamic improvements could be objectively measured.

First power-based mathematical model

In 1894, Émile Bourlet conducted the first quantitative study of forces acting on the cyclist, recognizing the passive resistance of the bicycle, rolling resistance, the impact of vibrations, and aerodynamic resistance as the main causes of energy losses (Bourlet, 1894). The mathematical theory proposed by Bourlet determined the quadratic relationship between aerodynamic resistance and velocity. The formula proposed by Bourlet was:

$$P = R \cdot V_g = [W(a + b \cdot V_g) + k \cdot A \cdot V_g^2] \cdot V_g$$

where P is the required power (W), R is the total resistive force on flat terrain (N), V_g is the rolling velocity (m/s), W is the weight, a is a coefficient related to rolling resistance (-), b is a coefficient related to both rolling resistance and vibrational resistance (s/m), k is a coefficient of aerodynamic resistance (-) and A is the frontal area (m²). For terrains with slope, Bourlet modified his model incorporating the effect of the inclination:

$$P = (R + W \cdot s) \cdot V_g = [W(a + b \cdot V_g) + k \cdot A \cdot V_g^2 + W \cdot s] \cdot V_g$$

where s represents the terrain slope (-).

To experimentally validate his model, Bourlet described two types of experiments. The first consisted of pedaling at constant velocity measuring slope, velocity, and power. To measure power, he used the *pedale dynamometrique*, a pioneering device patented by Maillard and Bardon in 1893, which allowed recording pedaling power (Bouny, 1899). The second experiment, which conceptually anticipates coast-down tests, sought an equilibrium velocity descending a constant slope. In this case, without pedaling, the cyclist reached an equilibrium velocity where the resistive forces (rolling, vibration, and aerodynamic) balanced with the propulsive force due to the slope, mathematically expressed as:

$$W(a + b \cdot V_g) + k \cdot A \cdot V_g^2 = -W \cdot s$$

where knowing the terrain slope s , the limit velocity V_g , the weight W and the frontal area A , the coefficients a , b and k were determined. Although Bourlet only theoretically described this second method, noting that Guye had performed such tests in 1893 (Guye, 1893), he laid the methodological

foundations for what would later become a standard technique in aerodynamic evaluation.

The aerodynamic resistance coefficient k , measured by Bourlet in the first experiment based on power pedal data, showed reasonable agreement with values measured in subsequent studies with different methodologies (Malizia & Blocken, 2020).

Wind Tunnel

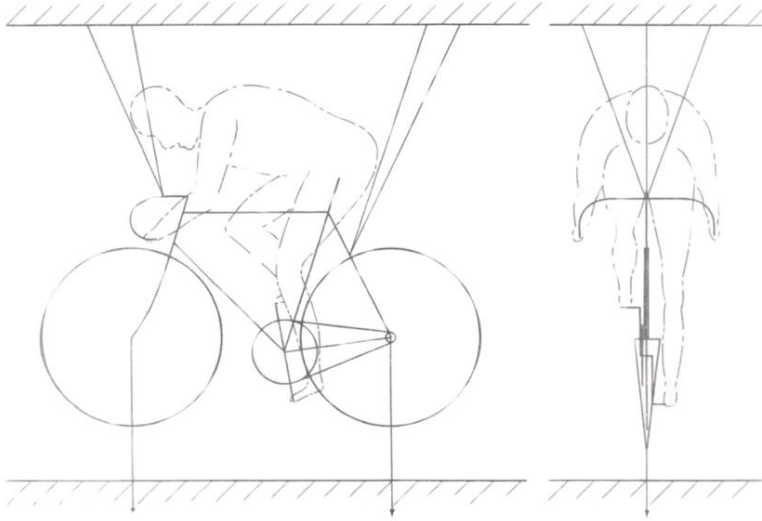
Although the first techniques for indirectly measuring aerodynamic resistance in cycling, based on validated mathematical models, provided useful estimates, their limitations motivated the search for more precise and direct methods. In this context, the prior development of wind tunnels for aeronautical applications enabled the adaptation of these facilities to cycling, offering a controlled environment where direct measurements of aerodynamic force could be carried out. The first experimental investigations in wind tunnels conducted by Kawamura (Kawamura, 1953, as cited in Kyle, 1979) and Nonweiler (1956) established the methodological foundations for assessing cyclist aerodynamics. Nonweiler's study was driven by the growing interest in human-powered flight, a field that highlighted the lack of data on the maximum power a person could produce.

Nonweiler used a closed-section wind tunnel where a bicycle was suspended at the center by cables attached to a balance mounted on the ceiling (Figure 8).

THEORETICAL BACKGROUND

Figure 8

Experimental design of the study on aerodynamic resistance with cyclists in a wind tunnel (Nonweiler, 1956)



Aerodynamic resistance was measured using a balance with a precision of ± 1 ounce, within a total force range between 6 and 17 pounds. However, difficulties were reported in obtaining stable measurements due to cyclist movement. To stabilize the bicycle, two weights were attached to cables running along the floor of the tunnel, connected to the wheel axles. Based on the balance measurements and the $C_D A$ equations:

$$\text{Drag Area} = \frac{\text{Drag}}{\text{Dynamic Head}}$$

and for power:

$$P = F_D \times V$$

where P is the required power (W), F_D is the drag force (N) and V is the relative flow velocity (m/s). Dynamic pressure is calculated as:

$$\text{Dynamic Head} = \frac{1}{2} \rho V^2$$

where ρ is air density (kg/m^3), which under standard sea level conditions is reformulated as:

$$\text{Dynamic Head} = 25.6 \left(\frac{1000}{V} \right)^2$$

to obtain the power required to overcome aerodynamic resistance as:

$$P = 0.00256 \times V^3 \times \text{Drag area}$$

Nonweiler was the first to quantify the proportional contribution of the cyclist's body to total aerodynamic resistance, determining that it accounted for between 60% and 82% depending on the posture adopted. Repeated tests with one of the subjects suggested that the overall measurement precision for aerodynamic resistance was approximately $\pm 3\%$.

Towing

The analysis of aerodynamic phenomena in cycling has evolved through theoretical and experimental approaches. Di Prampero et al. (1979) established quantitative relationships between aerodynamic resistance and the cyclist's metabolic cost, integrating variables such as body mass, environmental conditions (pressure and temperature), and terrain inclination. This study demonstrated how these factors interact in the production of mechanical power, establishing a predictive framework for the optimization of sports performance.

To measure these effects, they applied an experimental methodology that combined direct measurements and mathematical modeling through the towing technique. Developed as an alternative to wind tunnel tests, which presented certain limitations, this technique offered the advantage of testing under real cycling conditions. This technique, with precedents in the previous works of Sharp (1896) and Chandler and Chandler (1910), documented by Whitt (1971), allowed Di Prampero to obtain direct empirical data providing numerical values for the coefficients of his equations, thus obtaining a predictive model of practical use. On the other hand, although it corrected some of the limitations of laboratory tests, it introduced new limitations such as the turbulence generated by the towing vehicle.

Their experimental technique consisted of towing two cyclists on bicycles at stable speeds (5-16.5 m/s) under controlled conditions on the Monza racing circuit. The subjects maintained an aerodynamic position while being towed using a 25-meter-long nylon cable, a distance calculated to minimize the turbulence generated by the towing vehicle. The traction force was determined through a dynamometer attached to the cable. The measurements were carried out in both directions to compensate for the

THEORETICAL BACKGROUND

slight inclination of the circuit, applying the corresponding corrections to obtain the traction resistance on flat terrain.

The study of the data through linear regression allowed for determining the essential equation:

$$RT = 3.2 + 0.19v^2$$

where RT is the total resistance (N) and v the air velocity (m/s). In this expression, the constant term 3.2 (N) corresponds to rolling resistance, while the term proportional to the square of velocity represents aerodynamic resistance.

Di Prampero expanded this model to incorporate additional variables such as barometric pressure PB (mmHg), temperature T (K), body surface area SA (m²), total weight P (kg) and terrain inclination i (-), developing generalized equations both for mechanical power W (W):

$$W = 4.5 \times 10^{-2} P \dot{s} + 4.1 \times 10^{-2} \cdot (PB/T) SA v^2 \dot{s} + 9.8 P i \dot{s}$$

as well as for energy expenditure:

$$VO^2 = 8.6 \cdot 10^{-3} P \dot{s} + 7.8 \cdot 10^{-3} SA \cdot (PB/T) v^2 \dot{s} + 1.87 P i \dot{s}$$

where $\dot{s}$ represents ground speed (m/s). In these expressions, the terms that include $(PB/T) SA v^2 \dot{s}$ evidence the importance of the aerodynamic factor, since SA acts as a measure of the effective frontal area combined with the drag coefficient (C_D).

This relationship is supported by the empirical constants and aligns with the theoretical formulation of the aerodynamic drag force D (N):

$$D = 1/2 C_D A_p \rho v^2$$

recognizing that density ρ is proportional to (PB/T) . Under the experimental conditions employed, it was observed that the product $C_D A_p$ behaved almost constantly, being defined as an aerodynamic factor k as a function of PB and T through the relationship:

$$k = 0.0725 (PB/T)$$

This approach facilitated the indirect quantification of the contribution of aerodynamic resistance as a function of environmental conditions, being integrated into the term $(PB/T) SA v^2 \dot{s}$ of the general equations.

The experimental verification of the theoretical model was based on the contrast between the model's predictions and Eddy Merckx's hour record, set in Mexico City at 2230 meters above sea level. The analysis revealed that the optimal balance between physiological and environmental

parameters would be reached at altitudes between 3000-3500 meters, a range where the aerodynamic benefits derived from the decrease in atmospheric density would counteract the limiting effects of the decrease in maximum oxidative capacity.

Coast-Down

In the seventies, new techniques were explored to evaluate aerodynamic resistance as alternatives to traditional wind tunnel tests. Although these laboratory procedures were considered a reference standard, they had limitations such as the absence of rotational movement of the wheels, changes in airflow due to proximity to the ground, and a position that did not simulate real pedaling. Faced with these limitations and driven by technical advances in velocity measurement that improved reproducibility, the deceleration method was developed. This method is characterized by its simplicity, low cost, and capacity to calculate both aerodynamic and rolling resistance in real pedaling situations simultaneously.

This approach, which is based on Newton's second law:

$$\sum F = m * a$$

where $\sum F$ is the sum of all forces acting on an object (N), m is the weight (kg), and a is the acceleration (m/s^2), had already been previously employed in the transport sector, demonstrating effectiveness in the assessment of aerodynamic resistance in cars (White & Korst, 1972). In these cases, the coast-down test is based on the velocity-time curve derived from the equations of motion, using instruments such as accelerometers, tachometers, and odometers to record instantaneous deceleration, velocity, and distance.

In tests with cyclists, de Groot et al. (1995) used cycle computers to record velocity in deceleration tests. However, as indicated by Tengattini & Bigazzi (2018), their proposal presents difficulties, as in this case each bicycle would have to be instrumented before the test. Additionally, commercial cycle computers present resolution errors at low velocities, which affects the precision of the records. To avoid these limitations, in another study Waltham and Copeland (1999) manually recorded velocity using an audio recorder.

THEORETICAL BACKGROUND

Kyle and Burke (1984) also carried out an experiment in deceleration tests in which cyclists descended a slope and stopped on flat terrain. The initial velocity was measured using two timing bands on the ground, and the total distance traveled until stopping was recorded. The equation to describe the braking distance was:

$$x = \frac{m}{2c_2} \ln \left(\frac{-mgG + c_0 + c_2(v_0 - w)^2}{-mgG + c_0 + c_2w^2} \right) + \frac{mw}{\sqrt{c_2(-mgG + c_0)}} \left(-\operatorname{atan} \left(\frac{-w\sqrt{c_2}}{\sqrt{-mgG + c_0}} \right) + \operatorname{atan} \left(\frac{c_0 - mgG + c_2v_0^2}{-mgG + c_0} \right) \right)$$

where m is the weight of the cyclist and the bicycle (kg), c_0 (N) and c_2 (kg/m) are the parameters of rolling resistance and aerodynamic resistance, g is the gravitational acceleration (m/s²), G is the slope of the route (-), v_0 is the initial velocity of the bike (m/s) and w is the wind velocity (m/s).

In addition to these tests that were conducted outdoors and downhill, Kyle (1979) also carried out deceleration tests indoors and on level ground, which allowed for more controlled records, consequently, more reproducible, although less representative of real cycling.

In subsequent research, Kyle (1988b) refined his original mathematical model in relation to rolling resistance F_{rr} (N). His initial simplified model expressed this resistance as:

$$F_{rr} = N \cdot C_{rr}$$

where N is the number of wheels (-) and C_{rr} is the basic coefficient of rolling resistance (-), assuming that it was independent of velocity. However, his experiments revealed more complex behavior. To capture this reality, Kyle developed an alternative model that added two components:

$$F_{rr} = N \cdot C_{rr} + N \cdot C_{rr,2} \cdot V_g$$

The first term ($N \cdot C_{rr}$), represents the static component of rolling resistance, caused mainly by the basic deformation and hysteresis of the wheel material that occurs even at very low velocities. The second term ($N \cdot C_{rr,2} \cdot V_g$), introduces the dynamic component that increases linearly with velocity V_g (m/s), capturing additional phenomena such as impacts with

surface irregularities and viscoelastic effects that depend on the rate of deformation, where $C_{rr,2}$ is the dynamic coefficient of rolling resistance (s/m). This distinction between static and dynamic components allowed modeling with greater precision the real physical behavior of rolling resistance.

Mathematical Models Based on Power

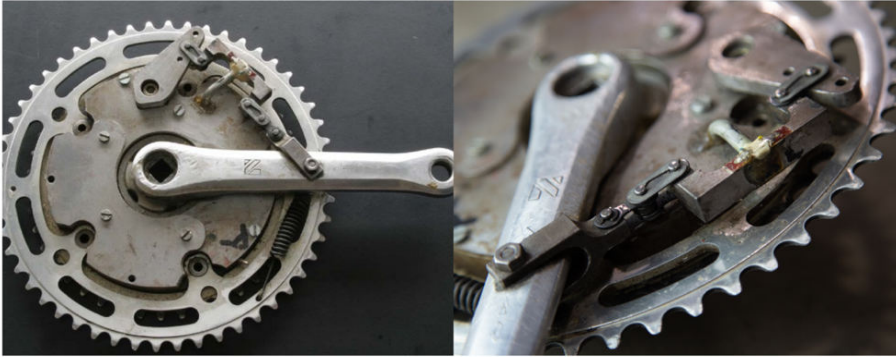
After the first methods of aerodynamic assessment such as wind tunnels, towing, and deceleration, the arrival of reliable commercial power meters marked the beginning of a new period in which measurements in real situations became more accessible.

The basic principle of using direct power measurement to study aerodynamics was not recent since, as mentioned, in 1894 Bourlet had based his experiments on the *pedale dynamometrique*. However, the technological restrictions of that period limited the accuracy and usefulness of the method.

The development of the SRM power meter (Schoberer Rad Meßtechnik, Jülich, Germany) created by Ulrich Schoberer during the 1980s marked the beginning of the new era in power measurement in cycling (Figure 9). This system, which used strain gauges incorporated into the bottom bracket, made it possible to directly quantify the force exerted during pedaling. However, the first versions of the SRM were expensive, heavy, and had low sampling frequencies.

Figure 9

First prototype of a cycling power meter with measurement in the spider



Note. The device was designed by Ulrich Schoberer in 1986. Composite image showing a general view on the left and a detail of the mechanism on the right (SRM GmbH, n.d.).

Throughout the 1990s, advances in electronics and signal processing resulted in the appearance of systems such as the SRM Professional, capable of recording data with errors below 2.5% and sampling frequencies of up to 5 Hz. This technological progress allowed revisiting the conceptual approach that Bourlet had initiated a century earlier.

In this context, Grappe et al. (1997) developed a methodology to determine C_{DA} and C_{rr} through direct power measurements in field conditions. For their experiments they used the "Max One" power meter (Look SA, Nevers, France). This power meter consisted of a 230 g hub for the rear wheel that was equipped with a torsion axle. When the wheel moved the hub during pedaling, the axle deformed proportionally to the torsion load. The moment of force τ (N·m), was quantified using a strain gauge, while the angular velocity ω (rad·s⁻¹) was measured at a frequency of four times per wheel revolution. The power expressed in watts represented the product of both parameters (τ and ω). The information was transmitted to a cycle computer via a cable, calculating the external power P_{ext} (W) as the average of eight consecutive revolutions.

Before their aerodynamic experiments, Grappe et al. (1997) performed a validation of the Max One power meter. To do this, they conducted tests on a laboratory treadmill (Gymrol, Super 2500), comparing the device's

measurements with reference values P_{ref} (W) calculated from fundamental physical principles:

$$P_{ref} = m g Vc \sin \alpha + Vc C_r m g \cos \alpha$$

Where m is the total mass (kg), g the gravitational acceleration (m/s^2), Vc the cyclist's speed (m/s), α the slope of the treadmill (rad), and C_r the coefficient of rolling resistance (-). They found a significant correlation ($r = 0.98$, $p < 0.001$), although they identified a systematic error. The device overestimated power below 151 W and progressively underestimated it above this value. They applied correction factors to compensate for these deviations in their subsequent measurements.

The aerodynamic methodology of Grappe et al. (1997) is based on the physical principle that, at constant speed, all the power generated by the cyclist is used to overcome resistive forces:

$$RT = P_{ext}/Vc^{-1}$$

where RT represents the total resistance (N). This resistance includes aerodynamic and rolling components:

$$RT = 0.5\rho AC_d Vc^2 + C_r m g$$

where ρ is the air density (kg/m^3), A is the frontal area (m^2) and C_d the aerodynamic resistance coefficient (-), with constants a and b defined as:

$$a = 0.5\rho AC_d$$

$$b = C_r m g$$

allowing the equation to be simplified to:

$$RT = aVc^2 + b$$

They conducted their experiments in an open velodrome of 453.89 m (Besançon, France) with a resin surface, under controlled conditions (barometric pressure = 756 mmHg, temperature = 12°C). For each of the four positions analyzed, the cyclist performed an incremental record of twelve laps at different speeds, starting at 5.5 m/s and increasing by 0.5 m/s each lap.

THEORETICAL BACKGROUND

When plotting RT against Vc^2 , they obtained linear relationships ($r = 0.90-0.95$, $p < 0.001$) whose slopes allowed them to directly calculate the AC_d :

$$AC_d = a/0.5\rho$$

Additionally, the intercept of this relationship was directly associated with rolling resistance. In this way, the method offered a comprehensive view of the components that affect performance, allowing identification of not only how posture influences aerodynamics, but also the behavior of the rolling coefficient.

A year later, Martin et al. (1998) conducted a study that validated a mathematical model to predict power developed in road cycling. In this work, they addressed the accuracy of the SRM power meter, finding that this device systematically overestimated power. However, they determined that this overestimation did not represent an instrument error but rather reflected the energy losses of the transmission system.

The SRM measures power at the crankset axis, before energy is lost through the chain and other components due to friction. Martin et al. (1998) estimated that these losses were approximately 2.36%, which is equivalent to a transmission efficiency of 97.7%. To validate the SRM as a measuring instrument, the authors carried out a protocol comparing it with the reference standard, a Monark cycle ergometer. This mechanical ergometer, based on a friction brake system, determines power directly from the product of the applied force (using known weights) and the pedaling cadence. The validation consisted of controlled tests in which cyclists pedaled at different power levels (45, 90, 135, 180, 225, and 270 W) on the Monark, simultaneously recording the values on the SRM.

Based on these previous validations, Martin et al. (2006a) developed the power-based aerodynamic assessment methodology. They employed a dynamically calibrated SRM Professional, which recorded data at 5 Hz, and explicitly incorporated the transmission efficiency factor ($E = 0.977$) in their equation:

$$P \times E - \frac{\Delta PE}{\Delta t} - \frac{\Delta KE}{\Delta t} = C_D A \times \left(\frac{1}{2} \rho S_a^2 S_g \right) + \mu \times (S_g F_N)$$

where P is the measured power (W), $\frac{\Delta PE}{\Delta t}$ and $\frac{\Delta KE}{\Delta t}$ the changes in potential energy (J) and kinetic energy (J), S_a the air speed (m/s), S_g the ground speed (m/s), and F_N the normal force (N).

The method was characterized by the two-step analytical process. First, they established initial values of $C_D A$ and μ (global friction coefficient that includes both rolling resistance and bearing friction) for each cyclist using multiple linear regression. Then, based on the physical principle that μ should be constant for a specific combination of tire and surface, they averaged this value across all cyclists and established it as a constant. Finally, they recalculated the individual $C_D A$ values through simple linear regression.

To validate their method, they directly contrasted the $C_D A$ values obtained in the field with measurements made in a wind tunnel. The results revealed high concordance with values of $0.258 \pm 0.006 \text{ m}^2$ in the field versus $0.261 \pm 0.006 \text{ m}^2$ in the wind tunnel, without statistically significant differences ($p = 0.53$).

Martin et al. (2006a) expanded their methodology to address non-stationary situations. This method made it possible, based on power-time data and previously established aerodynamic parameters, to predict speed during maximum accelerations. In this model they considered the moment of inertia of the wheels.

Subsequently, they adapted their methodology to be applied both in outdoor road conditions and indoor velodrome conditions, providing specific instructions for each environment (Martin et al., 2006a). For the road tests, they developed a protocol that considered elements such as terrain slope, wind speed, and speed variations. In the velodrome, they made modifications that took into account the geometry of the track.

THEORETICAL BACKGROUND

These modifications were based on mathematical corrections to compensate for the effects of velodrome curves. The authors acknowledged that the angle of inclination causes the center of mass to travel a path with a smaller radius than the wheels when a cyclist is navigating a banked curve. This results in a difference between the measured wheel speed and the center of mass actual speed which is crucial for computations. The tracks geometry the height of the center of mass (estimated by saddle height) and the angle of inclination obtained from the curves radius and speed were all taken into account in their calculations to describe this phenomenon. The normal force on the track was calculated as the vector sum of weight and centripetal force, which allowed more precise estimates of rolling resistance on banked curves.

Additionally, they created a spreadsheet that automated the calculations, making it easier for coaches and cyclists to calculate the C_{DA} using six records in field tests. In this tool, they identified that the complete two-step procedure (in which μ is determined first and then C_{DA}) was effective with large volumes of data; however, μ tends to be unstable when analyzed with few points. For this reason, in the spreadsheet, default values of μ were assigned (0.0025 for velodromes and 0.004 for smooth roads and higher values for rougher surfaces), thus avoiding the first step of the regression and allowing a more robust calculation of C_{DA} with little data.

The results were verified using the coefficient of determination (R^2) of the linear regression performed to determine the C_{DA} . According to Martin et al. (2006a), this value had to be 0.98 or higher to consider the data reliable, which would confirm that the measurements followed the aerodynamic behavior expected according to the theoretical model.

On the other hand, the Virtual Elevation (VE) method, developed by Robert Chung in the early 2000s and formalized in 2012 (Chung, 2012), represents an evolution in cycling aerodynamic assessment methods based on power data. Unlike previous methods that required controlled conditions, this approach allows aerodynamic evaluation in a greater variety of real environments. Its implementation in the Golden Cheetah performance analysis software for the first time in its version 2.0.0 through the Aerolab chart has facilitated dissemination among researchers, coaches, and athletes.

The fundamental principle of the VE method consists of using power, speed, and acceleration data to calculate a virtual elevation profile, which is the elevation that the cyclist would have experienced considering the power generated and the resistances of the system. Chung (2012) reformulated the general power equation for cycling to solve for the slope at each point:

$$s = \frac{P}{m \cdot g \cdot v} - C_{rr} - \frac{a}{g} - \frac{C_d A \cdot \rho \cdot v^2}{2 \cdot m \cdot g}$$

where s is the slope (-), P is the power (W), m the total weight (kg), g the gravitational acceleration (m/s^2), v the speed (m/s), C_{rr} the coefficient of rolling resistance (-), a the acceleration (m/s^2), $C_d A$ the drag area (m^2) and ρ the air density (kg/m^3).

Once the slopes are calculated instant by instant, they are numerically integrated along the distance traveled to reconstruct the complete virtual elevation profile. This integration is performed by summing the elevation increments ($\Delta h = s \cdot \Delta d$) in each sampling interval, where Δh is the change in altitude (m), s is the estimated slope, and Δd the distance traveled in that interval (m). The resulting profile represents the accumulated virtual elevation along the route.

The process involves iteratively adjusting the C_{DA} and C_{rr} values until the virtual elevation profile meets some known condition. A particular case used is that of a closed circuit, where the imposed condition is that the profile at the beginning and end of the lap has a net elevation gain of zero.

One of the methodological characteristics of the approach proposed by Chung is its ability to simultaneously estimate C_{DA} and C_{rr} from the analysis of the virtual elevation profile. This separation is possible because both parameters affect the calculated slope in differentiated ways. Aerodynamic resistance depends on the square of speed ($\propto v^2$), while the component associated with rolling presents a weaker dependence, which in a simplified manner can be modeled as constant with respect to speed.

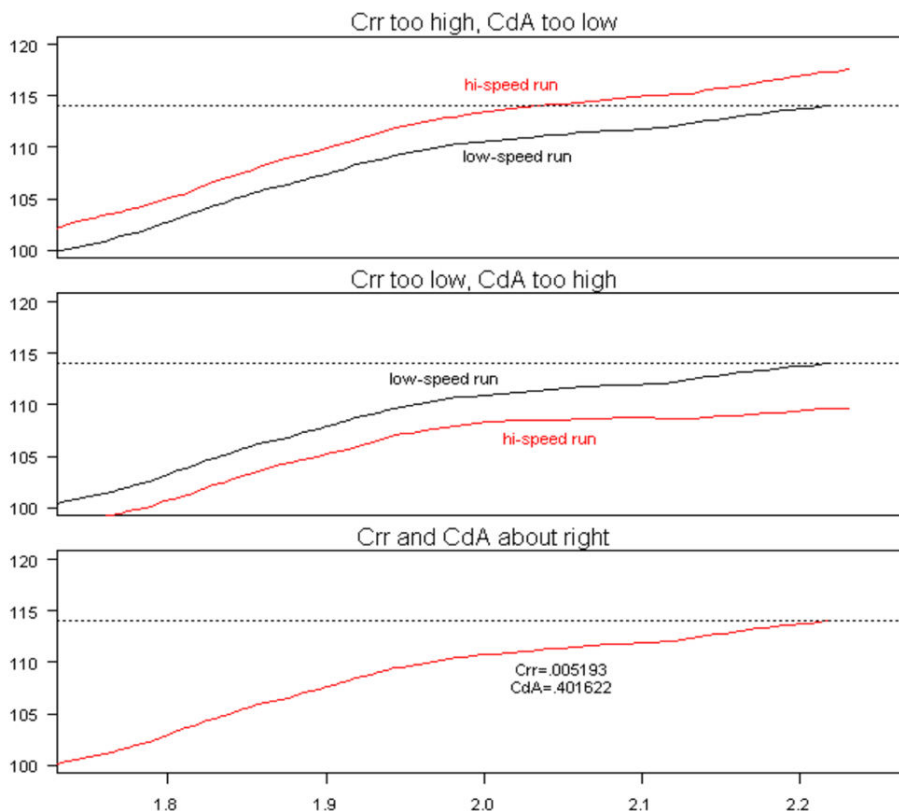
The mathematical formulation of the model allows exploiting this difference. When incorrect C_{rr} values are used, the effect on the virtual elevation profile manifests as a uniform displacement of the entire profile, regardless of speed variations, generating a systematic positive or negative slope. In contrast, errors in the estimation of C_{DA} cause distortions whose

THEORETICAL BACKGROUND

magnitude is proportional to the square of the speed, more notably affecting those sections of the route where the cyclist travels at higher speed. This divergence in behavior allows iteratively adjusting both parameters until achieving the superposition of virtual profiles obtained at different speeds, or the coincidence of the simulated profile with the real elevation profile (Figure 10).

Figure 10

Graphical representation of Virtual Elevation (VE) method



Note. Discrepancies between reconstructed elevation profiles at different speeds allow the identification of errors in the estimation of drag area (C_{dA}) and coefficient of rolling resistance (C_{rr}) (Chung, 2012).

The VE method can be carried out using different protocols. Chung's original method is performed on a closed circuit with several laps, ideally

with elevation variations that cause changes in speed and power to facilitate the separation of C_{DA} and C_{rr} . The adjustment condition is that the net elevation be equal to zero, which is given by the protocol of several laps in a closed circuit.

On the other hand, the Shen method, developed by Andy Shen as an extension of the Chung method, consists of performing a route on flat terrain in a single direction with a pattern of constant acceleration or deceleration so that speeds are systematically distributed from lower to higher (or vice versa) along the route. When incorrect values of C_{rr} and C_{DA} are used, the virtual elevation profile shows an arched shape. This method is an alternative in conditions where it is not possible to use a closed circuit.

Another alternative is the climbing method. Three ascents are performed at different speeds: low, medium, and high. The resulting virtual elevation profiles are adjusted until they match each other.

Lastly, and like the climbing method, the deceleration method is proposed, which consists of performing different descents in one direction. This is an applicable alternative when a power meter is not available, since zero power is assumed.

All these variants maintain the fundamental requirements of the method: constant position, avoiding environments with wind, and not using the brakes during the route. Generally, a speed sensor, power meter (except in the deceleration alternative), and barometric altimeter is required.

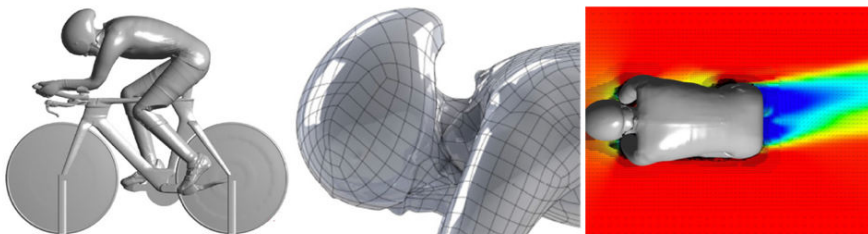
Dyer and Disley (2017) validated the VE method in an indoor velodrome evaluating different prosthesis designs in cyclists with unilateral transtibial amputation. Their study directly compared the C_{DA} calculated by VE with the C_{DA} calculated in wind tunnel tests, finding coefficients of variation of 2-3% for VE versus 0.7-0.9% for wind tunnel, with a systematic difference of approximately 0.03 m² in absolute values. On the other hand, Maier et al. (2018) verified the usefulness of VE for determining the C_{rr} of different tires, detecting statistically significant differences that translated into speed variations of up to 3.2% on flat terrain and 2.4% on slopes of 10%. In the formalization document of the VE method, Chung (2012) reports coefficients of variation of 0.3%, with a standard deviation of 0.0006 m² for an estimated C_{DA} of approximately 0.2 m², which demonstrates the precision of the method in aerodynamic evaluations.

Computational Fluid Dynamics

From 2010 onwards, CFD emerged as a fundamental tool in aerodynamic studies of cycling, overcoming the methodological limitations of traditional methods. Unlike other techniques such as wind tunnel testing, CFD made it possible to visualize and quantify the flow phenomena generated around the cyclist (Figure 11).

Figure 11

Computation Fluid Dynamics (CFD) process for aerodynamic analysis in cycling



Note. The figure shows the model geometry (left), the mesh detail used for domain discretization (center), and the normalized horizontal velocity distribution map (right). Adapted from Chi et al. (2020).

Although CFD as a commercial analysis tool was developed in the 1980s, its specific application to sports did not begin until the 1990s. Initially, it was an exclusive discipline mainly used in turbomachinery, aerospace, and combustion fields. During the 1990s, it became consolidated thanks to software such as ANSYS Fluent, which made it accessible to engineers and allowed its use in various sports (Hanna, 2012).

At that time, the computational limitations greatly restricted the use of CFD in cycling, where modeling the complex cyclist-bicycle geometry

together with the leg and wheel motion represented a significant challenge. As a result, aerodynamic studies in cycling continued to rely mainly on classical experimental methods such as wind tunnel testing. Later, advances in computational capacity facilitated the implementation of CFD in sports applications, allowing increasingly complex geometries to be addressed (Hanna, 2012).

One of the pioneering studies in the application of CFD to cycling was conducted by Defraeye et al. (2010a). This research systematically compared several turbulence models and boundary layer modeling methods, contrasting the CFD simulation results with real measurements. The authors found that the Shear Stress Transport (SST) $k-\omega$ turbulence model combined with Low-Reynolds Number Modeling (LRNM) provided superior accuracy in predicting flow behavior and separation compared to the standard $k-\epsilon$ models that used wall functions.

In the same study, Defraeye et al. (2010a) not only validated the global forces but also analyzed and compared surface pressures at 30 specific locations on the cyclist's body. According to the authors, surface pressure measurements provide additional information for drag assessment. This is because a correct match between drag values obtained by CFD and experimental measurements does not independently guarantee that the flow field is accurately replicated, since drag is the result of the combination of surface pressures.

This approach was expanded by the same authors in a subsequent investigation (Defraeye et al., 2010b). In this study, a scale model (1:2) equipped with 115 pressure taps was used. The results confirmed the superiority of the SST $k-\omega$ model combined with LRNM while simulations based on Large Eddy Simulation (LES) offered similar accuracy but at a higher computational cost.

From a methodological point of view, the CFD applications of that period were characterized by using turbulence models based on Reynolds-averaged Navier-Stokes equations (RANS), especially the standard $k-\epsilon$ model with wall functions. Although these models were computationally efficient, they had restrictions in accurately anticipating flow separation in complex geometries with adverse pressure gradients as demonstrated in the research by Defraeye et al. (2010b).

THEORETICAL BACKGROUND

At this stage, progress was made in meshing methods, especially in the boundary layer solution. Blocken et al. (2013) implemented meshing techniques with extremely precise resolution in the vicinity of surfaces using cells of about 30 micrometers. This made it possible to obtain y^+ values less than 1 across the entire surface of the cyclist, where y^+ represents the dimensionless distance from the wall normalized with the friction velocity and the kinematic viscosity of the fluid. Keeping y^+ below 1 allowed for directly resolving the boundary layer without the need to use wall functions, which in turn facilitated more accurate prediction of the flow separation point, modeling the transition from laminar to turbulent flow, and more precisely estimating the distribution of surface pressure.

During this period, several methodological restrictions were detected in CFD applications in cycling, such as high computational costs, the need to simplify dynamic elements, and challenges in verifying results under real cycling conditions, in addition to restricted integration with other relevant physical phenomena. However, CFD fundamentally changed aerodynamic research in cycling by overcoming many of the limitations of traditional experimental methods. According to Defraeye et al. (2010a), although conventional experimental methods generally provide global force measurements, CFD facilitates the exact quantification of local contributions from each element or anatomical area to total aerodynamic resistance, which allows for optimizing aspects such as arm placement or helmet configuration. Additionally, CFD offers a complete three-dimensional representation of the flow field that facilitates the identification of vortical structures and drag-generating mechanisms that are difficult to capture through traditional experimentation. On the other hand, Blocken et al. (2013) highlight the usefulness of CFD for simulating complex dynamic conditions such as interactions between cyclists or the variable effects of crosswinds, situations that are difficult to replicate under controlled experimental conditions.

Particle Image Velocimetry

Particle image velocimetry (PIV) represented an advance in the aerodynamic study of cycling by overcoming some of the restrictions of CFD. This experimental methodology allows direct visualization of vortical structures and transient flow phenomena, aspects that numerical models may not capture with precision. Additionally, its non-invasive implementation avoids disturbances generated by physical probes used in traditional methods.

The foundation of PIV is based on the illumination of a flow plane through a pulsed laser that captures successive images of tracer particles found in that same plane. Through cross-correlation algorithms, the movement of particle groups between successive images is established. By knowing the temporal range between laser pulses, the instantaneous velocity field in the measurement plane is determined.

The initial versions of the PIV method used photographic film, which considerably restricted its practical application. The digital revolution with the invention of high-resolution charge-coupled device (CCD) cameras facilitated the capture and processing of images. This drove the evolution of PIV as an experimental instrument in fluid mechanics.

Two-dimensional PIV (2D-PIV) provided information on two velocity components in a single plane. The progress towards three-dimensional PIV (PIV3C) made it possible to identify the three velocity elements in a plane through the use of two cameras examining the same area from different angles.

In one of the first applications of the PIV3C method in the analysis of aerodynamics in cycling, Chabroux et al. (2010) used this methodology to explain the vortical flow in the wake of various helmet designs.

The main limitation of PIV was its restriction to measurements in specific planes, which prevented capturing the complexity of three-dimensional flows generated around a cyclist. Although PIV3C allowed recording the three velocity components in a plane, it did not allow obtaining volumetric measurements. Large-scale vortical structure reconstruction was challenging because the measurement zone was dependent on the lasers power the cameras resolution and the density of the tracer particles. This restricted the analysis to comparatively small areas. Tomographic or

volumetric PIV which measures the three velocity components in a three-dimensional volume was developed in response to these constraints.

Tomographic PIV recreates the three-dimensional arrangement of particles in an illuminated volume using a variety of cameras. Through tomographic reconstruction algorithms, a three-dimensional map of light intensity is created, representing the spatial distribution of the particles. Temporal monitoring of these distributions facilitates the calculation of the complete three-dimensional velocity field.

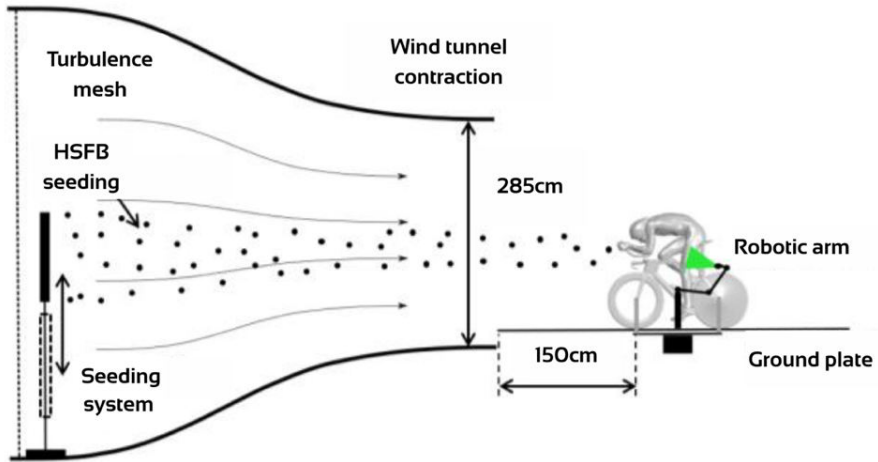
However, the application of tomographic PIV at full scale presented the challenge of illuminating and visualizing volumes much larger than those typical in other laboratory applications. Traditional tracer particles (oil droplets) did not provide sufficient light scattering to be detected in large volumes. Additionally, the particle density necessary for accurate tomographic reconstruction was difficult to achieve in large volumes.

The solution to this problem came with the introduction of helium-filled soap bubbles (HFSB) as tracers. These bubbles combine two properties: high light reflectivity that guarantees high-quality images and neutral buoyancy that allows them to faithfully follow the flow trajectory without introducing additional inertia.

The work of Terra et al. (2018) was based on the tomographic PIV technique to perform large-scale measurements, analyzing a transverse plane behind the extended leg of a 1:1 scale mannequin of professional cyclist Tom Dumoulin. The integration of volumetric PIV with robotic systems represented another significant methodological advance (Figure 12). The study conducted by Jux et al. (2018) implemented coaxial volumetric velocimetry (CVV) coupled to a robotic arm, allowing the characterization of the complete flow field around a 1:1 scale cyclist mannequin.

Figure 12

Experimental design scheme in wind tunnel of the robotic volumetric Particle Image Velocimetry (PIV) system

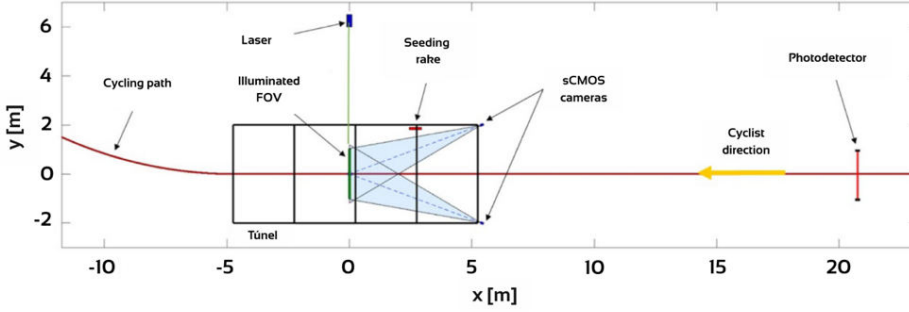


Note. From Terra (2020).

The PIV method has not only allowed the visualization of flow fields but has also evolved towards the quantitative measurement of aerodynamic drag in moving cyclists. The Ring of Fire (RoF) method developed by Terra et al. (2017) has considerably expanded the analysis capabilities of PIV by employing momentum conservation principles to directly determine aerodynamic forces (Figure 13).

Figure 13

Schematic representation of a Ring of Fire (RoF) experimental design



Note. From Spoelstra et al. (2021).

The theoretical basis of this method is founded on the momentum conservation equation applied to a control volume around the cyclist. This equation is expressed as:

$$D(t) = \rho \iint_{S_1} U_{\infty}^2 dS + \iint_{S_1} (p_{\infty} - p_1) dS - \rho \iint_{S_2} U_{\infty}^2 dS + \iint_{S_2} (p_{\infty} - p_2) dS$$

where $D(t)$ represents the instantaneous drag force (N), ρ the air density (kg/m^3), S_1 and S_2 the control surfaces before and after the cyclist (m^2), U_{∞}^2 the free-stream velocity squared (m^2/s^2), p_{∞} the pressure in the free stream (Pa), p_1 and p_2 the pressures in the respective control surfaces (Pa), and dS the differential surface element (m^2).

Conceptually, this can also be understood as:

$$D = M_{upstream} - M_{wake}$$

where D is the drag force (N), $M_{upstream}$ represents the upstream momentum flow (before the cyclist) (N), and M_{wake} the momentum flow

in the wake (after the cyclist) (N). This equality comes directly from Newton's second law applied to the control volume. The difference between the momentum flows entering and leaving the volume must be equivalent to the external force exerted on the fluid, which is identical and opposite to the drag force felt by the cyclist.

The practical implementation of this equation requires a Galilean modification, moving from the laboratory context to the cyclist context. This transformation modifies an intrinsically non-stationary problem into a quasi-stationary one, which allows writing the equation as:

$$D(t) = \rho \iint_{S_1} (u_{env} - u_c)^2 dS + \iint_{S_1} (p_\infty - p_1) dS - \rho \iint_{S_2} (u_{wake} - u_c)^2 dS - \iint_{S_2} (p_\infty - p_2) dS$$

In this formula, u_{env} represents the ambient air velocity before the cyclist passes (m/s), u_c the cyclist's velocity (m/s), and u_{wake} the velocity in the wake after the cyclist passes (m/s).

The RoF method introduces significant variations compared to conventional PIV. While traditional PIV configurations maintain the object of study stationary within the field of view, RoF requires that the cyclist cross the measurement plane. This configuration requires precise synchronization of data acquisition, capturing the state of the flow before and after the cyclist passes. Additionally, data processing involves precisely defining the limits of the control volume, performing specific contouring of the wake, and adjusting the input surfaces to ensure mass conservation.

The experimental implementation of the RoF method, initially proposed by Terra et al. (2017) and subsequently applied to cycling by Spoelstra et al. (2019), was carried out using a large-scale stereoscopic PIV system, with measurement planes of approximately 2×2 m² with HFSB as tracers. The authors performed between 10 and 30 passes of the cyclist, averaging the results. They identified that the validity of the measurements is limited to a specific time window after the cyclist passes, before effects such as wake diffusion or its exit from the measurement field compromise the results.

Studies conducted using the RoF method by Spoelstra et al. (2019) demonstrated that the upright position generates between 20% and 35%

THEORETICAL BACKGROUND

more aerodynamic resistance than the time-trial position. Another finding was the identification of various vortical structures generated by different body parts. The study evidenced several vortices in the hip, head, shoulders, and arms. Additional structures were identified, such as the shoulder and arm vortex in the upright position, which are not found or are less notable in the time-trial position. This information is valuable for understanding how different body positions affect aerodynamic resistance.

Unlike observations from other studies conducted in wind tunnels (Crouch et al., 2014), the RoF method did not detect a clear cyclical variation in aerodynamic resistance dependent on the crank angle during pedaling. This suggests that, in real cycling conditions, wake diffusion and turbulent mixing might have a dominant effect over the instantaneous position of the legs.

Another notable application of the RoF method has been the study of the aerodynamic drafting effect between cyclists. Spoelstra et al. (2020) extended the basic principle to analyze the reduction of resistance when a cyclist rides in the wake of another. The results showed drag reductions between 27% and 66% for the drafting cyclist, depending on the longitudinal and lateral separations. It was observed that lateral distance impacts approximately three times more than longitudinal distance in drag reduction. In particular an aerodynamic benefit of roughly 1.3 % is produced by a 10 cm reduction in longitudinal distance whereas an increase of 3.9% is produced by a similar reduction in lateral distance. In events like track pursuit or team time trials these data are useful for maximizing team configurations. The study also demonstrated that the greater the C_{DA} of the leading cyclist, the greater the aerodynamic benefit obtained by the cyclist behind.

The RoF method has various limitations, such as the indirect estimation of the pressure term in the momentum conservation equation, which introduces uncertainties near the cyclist; however, its ability to combine quantitative drag measurements with the visualization of flow structures in real cycling conditions makes it a valuable tool for aerodynamic research applied to cycling.

Aerosensors

Technological advances in sensor miniaturization, computational processing capacity, and connectivity systems have enabled the manufacture of portable devices based on Pitot tubes, known as aerosensors, for aerodynamic evaluation in the field.

Traditional methods present limitations for widespread application. The wind tunnel, considered the reference standard in aerodynamic measurements, presents high operational costs and logistical complexities that restrict its use for many cyclists. Furthermore, the simulated conditions do not exactly reproduce environmental reality. Alternative methodologies such as towing, deceleration, or theoretical mathematical models solve some of these restrictions, although they introduce others. Towing and deceleration methods require specific experimental protocols that are difficult to apply, as well as specialized equipment, while mathematical models, despite being more accessible thanks to the generalization in the use of power meters, present significant methodological difficulties.

Mathematical models require post-data acquisition calculation procedures, involving a process that requires specific knowledge and considerable processing time. More significantly, these models present difficulties in accurately quantifying the relative wind vector experienced by the cyclist during the route. The formulas that establish aerodynamic resistance require an exact measurement of air velocity in relation to the cyclist, a value that usually varies continuously in field conditions due to factors such as variable wind patterns, turbulence phenomena, or topographical characteristics of the route. Traditional mathematical models accept constant air flow conditions or use values recorded at specific points along the route, which can compromise the validity of the results. In this context, aerosensors emerge as a technological alternative to previous methodological limitations. These devices address several challenges by offering direct measurements of relative wind, automating data management through computer programs, and displaying C_{DA} values in real time.

The automation of data processing eliminates the need for subsequent calculations, reducing the time between data acquisition and interpretation of results. On the other hand, the real-time visualization of the C_{DA} during the activity allows the cyclist to obtain immediate feedback on the

THEORETICAL BACKGROUND

aerodynamic effects derived from changes in position. This immediate response capability transforms aerodynamic optimization from a static process to a dynamic system. These devices represent a methodological change in aerodynamic study by allowing simple, accessible, and efficient evaluations, without requiring specialized technical personnel or professional equipment.

Aerosensors integrate various sensors, with their own processing algorithms, including a Pitot-static tube that measures the difference between dynamic pressure and static pressure. According to the principles of the Bernoulli equation, this difference allows calculating the relative air velocity:

$$U_{\infty} = \sqrt{\frac{2q}{\rho}}$$

where U_{∞} represents the free stream velocity (m/s), q corresponds to the dynamic pressure (difference between total and static pressure) (Pa) and ρ is the air density (kg/m³) (Le Méhauté, 1976).

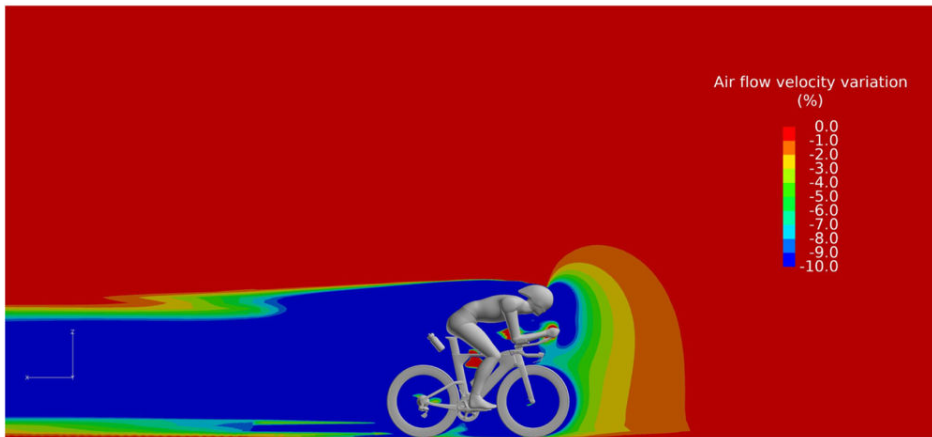
Additionally, these devices integrate barometers, thermometers, and humidity sensors that allow calculating air density, a critical parameter in determining the C_{DA} . As demonstrated by Millour et al. (2023), even small changes in these parameters can have a big impact on the C_{DA} values that are determined especially when the environment conditions are changing. By integrating accelerometers and gyroscopes it is possible to record changes in the bicycles speed inclination and orientation, information that is essential for distinguishing aerodynamic resistance from other resistive forces like gravity or inertial.

Aerosensors are mounted on the front of the bicycle, specifically on the bottom of the handlebar, using a specific mount. These instruments are linked with power and speed measurement systems, integrating the data into their calculation algorithms. Calibration protocols vary according to the specific device and are mainly necessary to correct the disturbance that the cyclist and the bicycle themselves generate in the air pressure field measured by the sensor (Figure 14). Kordi et al. (2021) describe a calibration process with the Notio device, consisting of two 3000-meter routes, following the manufacturer's instructions. After this initial calibration, the device

continuously records the relevant parameters during the activity and processes the data through proprietary algorithms, allowing specifically isolating the component corresponding to aerodynamic resistance.

Figure 14

Percentage variation field of airflow velocity relative to the undisturbed free-stream velocity



Note. The figure was obtained through Computational Fluid Dynamics (CFD) simulation. Provided by Notio Technologies (personal communication, November 2020).

The development of this technology dates back to 2006 with the iBike cycle computer (Velocomp LLC, Jupiter, USA), a precursor device that, without being an aerosensor, established the technological precedents. This type of device, also known as opposing force power meters (OFPM), emerged as an alternative given the interest in power measurement in contexts where direct force power meters (DFPM) such as SRM or PowerTap (SRAM, Chicago, USA), had a cost ranging between €1000 and €1500, and required periodic calibrations and maintenance. The iBike, with an approximate price of €400, incorporated a pressure sensor to indirectly determine the power developed by the cyclist, using a port for a wind sensor that anticipated aerosensor technology. According to the manufacturer's specifications, the system employed a mathematical model based on the

THEORETICAL BACKGROUND

equations of Martin et al. (1998), calculating aerodynamic, gravitational, and rolling resistance data to obtain power.

The iBike evolved into different devices such as iAero (2009), Newton (2011), and PowerPod (2016) (Figure 15). All these devices shared a fundamental limitation reported by Merkes et al. (2019), they used constant C_{DA} values in their power calculations, which generated significant estimation errors, particularly in real cycling conditions where position varies constantly. As the authors indicate, at speeds of 60 km/h, position changes can imply differences of between 25 and 190 W in the required power.

Figure 15

PowerPod device by Velocomp



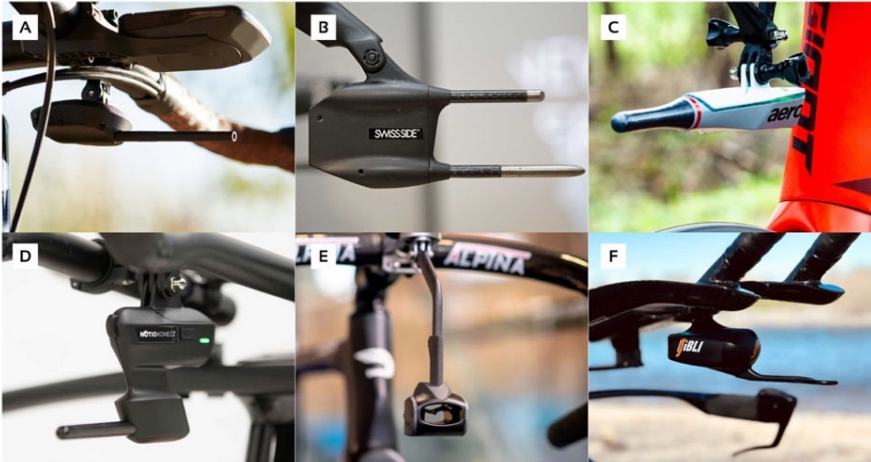
Note. The PowerPod is an opposing force power meter (OFPM) that can be considered a precursor of current aerosensors (Velocomp, n.d.a).

The limitations of OFPM in power determination, evident when compared to DFPM, led to a progressive commercial reorientation of the concept, evolving towards a device focused on aerodynamic assessment. This transition was coherent, as both approaches are based on the same principle, the processing of mathematical models based on the various resistances faced by the cyclist.

In 2018, the first aerosensors arrived with AeroPod (Velocomp LLC, Jupiter, USA), a new device that incorporated a Pitot-static tube for C_{DA} calculation (Figure 16). Scientific literature has offered varied conclusions regarding its accuracy. Fenre & Klein-Paste (2021) reported that the C_{DA} calculated with AeroPod during field tests on a straight, flat 400-meter road was consistent with the values obtained in the wind tunnel. However, Van Erp et al. (2021) identified limitations, particularly in the presence of crosswinds. Their analysis revealed that, after calibration at 14 m/s, AeroPod showed an increasing error reaching -2.51% at 20 m/s. The device exhibited inadequate wind speed measurement with yaw angles, with differences between the actual and measured speed ranging from -3.2% to 3.9% at an angle of 20°. These results questioned the device's reliability under real cycling conditions, considering that these variations in wind measurement directly translate into errors in C_{DA} calculation.

Figure 16

Aerosensors from six commercial brands



Note. A) AeroPod (Velocomp, n.d.b), B) C_DA-Meter v3 (Swiss Side, n.d), C) AeroPro (Aerolab, n.d), D) Notio Konect (Notio Technologies, n.d), E) Aerosensor (Aerosensor Tech, n.d), and F) GiBLI G10 (GiBLI Tech Inc., n.d).

The July 2017 acquisition of Alphamantis Technologies (Montreal Canada) by Garmin (Olathe USA) demonstrated the growing interest in aerodynamic assessment in cycling. This company created the Track Aero System (TAS) which Bouillod et al. (2015) scientifically validated. (2015) enabling C_DA computation in the velodrome. Unlike portable devices such as AeroPod, TAS operated through the installation of sensors on the track, processing data to provide a C_DA value per lap. This acquisition generated expectations regarding the development of a possible aerosensor called “Vector Air,” a product that would integrate Garmin Vector's power measurement technology, the brand's power meter, with real-time aerodynamic analysis based on Alphamantis' experience. Despite some information leaks in November 2019 about its possible launch, including details about its technical features and price, the product has never been commercially released.

During those years, several companies explored the development of aerodynamic sensors. The Swiss Side C_{DA} -Meter (Swiss Side, Thalwil, Switzerland) was announced at Eurobike 2018, a device that emerged as an evolution of another device called the *Instrumented Bike* that the same company had been developing since 2014 for the aerodynamic optimization of one of its wheel models. Its distinctive feature was a dual Pitot tube system, designed to address the limitations of single-tube devices. In this arrangement, the tube located at the top focused solely on calculating the yaw angle, establishing the direction of crosswind relative to the cyclist. Meanwhile, the second Pitot tube located at the bottom focused on measuring wind speed, offering an integrated data set for C_{DA} calculation. Although a prototype was used during the preparation for the 2017 Ironman World Championship in Kona, Hawaii, by the winner Patrick Lange, this device was never commercially released, but it continues to be used for aerodynamic testing both internally by Swiss Side and with their partners/customers.

The AeroPro device (Aerolab.tech, Calgary, Canada), also presented at Eurobike 2018, incorporated a three-hole Pitot probe that allowed direct measurement of the wind vector. The international patent WO 2017/197524 A1, whose inventors are Chris Morton and Kelly Zwarych, then owners of Aerolab.tech, describes a system with a technical configuration that matches the characteristics reported in the AeroPro technical document (Morton, C, n.d.). It describes a dynamic calibration method to correct the disturbance on the sensor. The device featured two differential pressure transducers connected to the three holes of the Pitot probe, enabling the measurement of both airspeed and yaw angle (Morton & Zwarych, 2017).

Another feature of the AeroPro system was its ability to evaluate both C_{DA} and C_{Tr} either simultaneously or independently. For C_{Tr} calculation, the device incorporated vibration sensors that measured the vibrations generated by the contact of the wheels with the surface, allowing adjustments according to terrain conditions. The system integrated multiple sensors including global positioning system (GPS), barometric altimeter, temperature and humidity sensors, inertial measurement unit (IMU), and differential pressure transducers.

THEORETICAL BACKGROUND

In field tests conducted by the company itself, AeroPro demonstrated the capability to detect aerodynamic changes such as a 6.5% reduction in aerodynamic drag after leg shaving. Independent scientific validation was presented in the form of a poster at a scientific conference by Girouard et al. (2019). This research, although focused on C_{rr} measurement, verified the device's ability to detect changes in tire-generated resistance at different pressures during outdoor tests. The researchers found that the device could measure variations in C_{rr} of 95.7% with tires at 70 psi and 119.6% with tires at 40 psi, taking 100 psi as the reference pressure. However, they identified significant sources of error that could influence C_{rr} calculations, including unintentional changes in cyclist position, wind yaw angle, and tire temperature. These methodological limitations suggest that, although the device showed sensitivity to detect variations in C_{rr} , its absolute precision could be compromised under real conditions. During the time that Aerolab.tech was active, the company chose a business model based on temporary rental of the AeroPro, rather than large-scale commercial distribution.

In July 2018, Notio Konect (Notio Technologies, Montreal, Canada) positioned itself as one of the first companies to bring to market a consumer device with the Notio aerosensor. This device integrates a Pitot-static tube for direct airflow measurement, complemented by a triaxial accelerometer, a triaxial gyroscope, a barometer, and humidity and temperature sensors. The relatively early commercial availability of this aerosensor compared to other models has facilitated its use in aerodynamic research in cycling.

Valenzuela et al. (2020) compared Notio with two methods for C_{DA} calculation, TAS and Martin, under indoor velodrome conditions. Their results demonstrated an almost perfect correlation with an intraclass correlation coefficient (ICC) of 0.99 for Notio with the two reference methods. However, this same study also identified a limitation of the device related to its sensitivity to detect small changes in C_{DA} .

The researchers observed that while Notio could detect large variations in the cyclist's position (0.072 m^2), it could not identify smaller changes, such as those produced by different types of helmets (0.008 m^2). This behavior is related to the typical error of measurement (TEM), which was 0.015 m^2 (90% confidence interval [CI]: $0.014\text{--}0.017$), representing

approximately 4.9% of the average measured C_{DA} value ($0.308 \pm 0.051 \text{ m}^2$). Both the TAS system and the mathematical model were able to identify the smaller aerodynamic improvements. Specifically, Notio provided slightly higher C_{DA} values ($0.308 \pm 0.051 \text{ m}^2$) than TAS ($0.300 \pm 0.051 \text{ m}^2$, $p < 0.001$) and the Martin model ($0.303 \pm 0.051 \text{ m}^2$, $p = 0.005$), although the effect sizes were trivial ($ES = 0.15$ and $ES = 0.09$, respectively). This slight tendency to overestimate C_{DA} represented an important limitation for the practical application of the device in indoor velodromes.

Kordi et al. (2021) conducted a study with elite cyclists in an indoor velodrome to evaluate the reliability and sensitivity of Notio in C_{DA} calculation. To this end, they carried out two experiments. In the first, they assessed intra- and inter-effort reliability, with an intra-effort coefficient of variation (CV) of 0.20% (0.16–0.69%), an absolute typical error of 0.0017 m^2 (0.0013 – 0.0023 m^2), and a standardized typical error of 0.13 m^2 (0.11 – 0.18 m^2). Inter-effort reliability showed a CV of 0.90% (0.46–1.52%) and an ICC of 0.99 (0.98–1.00), demonstrating high repeatability. In the second experiment, they evaluated sensitivity using discs of different diameters (5, 6, 8, and 10 cm) mounted on a one-meter rod attached to the bicycle to modify C_{DA} by known amounts. This demonstrated that Notio could detect changes as small as 0.002 m^2 (1.2% of total C_{DA}) and that the relationship between theoretical and measured changes was almost perfect ($R^2 = 0.996$), confirming the device's capacity to accurately quantify small aerodynamic variations under controlled conditions.

On the other hand, Van Erp et al. (2021) compared Notio with AeroPod in a wind tunnel at different speeds (8–20 m/s) and yaw angles (0–20°). The results showed that both devices required calibration to ensure accuracy at different speeds. After calibration at 14 m/s, they observed that Notio showed variations of only 0.22% up to 20 m/s, while AeroPod presented an increasing error with speed, reaching -2.51% at 20 m/s. An important finding was the identification of a limitation in accurately measuring wind speed with yaw angles. The authors found differences between the actual and measured speed ranging from 2.3% to 5.8% for Notio and from -3.2% to 3.9% for AeroPod, with the latter showing greater variability in its measurements. In addition, they demonstrated that the cyclist's position significantly affected the measurements, with differences of -5.2% in Notio

THEORETICAL BACKGROUND

(upright vs. aerodynamic position) and -5.8% (upright vs. optimized aerodynamic position), while for AeroPod these differences were -1.3% (upright vs. aerodynamic position) and -3.1% (upright vs. optimized aerodynamic position). This suggested the need to recalibrate before changing the cyclist's position to obtain accurate measurements.

Bruez et al. (2023) evaluated the reliability and sensitivity of Notio outdoors, compared with Aeroscale, another aerosensor model. The main difference between the two devices is that Aeroscale does not need to be linked to a power meter to calculate C_{DA} . The researchers used a disc protocol similar to that reported by Kordi et al. (2021), but on open roads instead of an indoor velodrome. The study reported high reliability for Notio ($ICC = 0.98$), while Aeroscale also showed good reliability ($ICC = 0.92$). Regarding sensitivity in detecting changes in C_{DA} , the result for Notio was 4.8%, while for Aeroscale it was 0.5%. These results contrast with the 1.2% value reported by Kordi et al. (2021) under indoor velodrome conditions.

An important finding was that the C_{DA} values displayed during pedaling fluctuated considerably (between 0.1 and 0.7 m²), even under apparently constant conditions. This represents a practical limitation of Notio for providing real-time C_{DA} calculations, according to the researchers. The study concluded that, to obtain reliable results outdoors, aerosensors should be used exclusively under highly controlled conditions.

Millour et al. (2023) evaluated the accuracy of cyclist performance modeling under uncontrolled outdoor conditions using Notio, comparing various methods of recording meteorological data. Unlike previous studies that directly assessed C_{DA} accuracy, this research analyzed the device from a functional perspective, indirectly validating its accuracy through power modeling under real conditions with eight rides of 9.2 ± 2.4 km with variable topographic profiles. The researchers incorporated the C_{DA} calculated by Notio and meteorological variables from three different sources (the Notio device itself, a portable Kestrel weather station, and the OpenWeather web portal) into the Martin mathematical model to calculate theoretical power.

The results showed notable discrepancies between the sources. The power calculated with Notio data exceeded the power measured directly by the power meter by 1 ± 4 W, while with Kestrel it was 7 ± 15 W lower, and with the OpenWeather portal it was 67 ± 111 W higher. The analysis

confirmed that the model based on Notio achieved a root mean square error (RMSE) of 12.8 W and R^2 of 0.77 ($p < 0.001$), validating its predictive capacity under real conditions.

Another important finding was the critical influence of relative wind on the model's accuracy. Simulations showed that variations of 4 m/s generated differences of up to 210 W in the calculated power, while temperature, pressure, and humidity had marginal effects (2–3 W). The imprecision of OpenWeather was mainly attributed to the fact that its anemometers operate at 10 meters above the ground, so they do not represent the aerodynamic conditions experienced by the cyclist.

As far as we know, the most recent study on Notio was published by Faulkner et al. (2024), who investigated the reliability of the device and its application to optimize performance in time trials through the analysis of the interaction between physiological economy and aerodynamics. Nine trained cyclists completed 3200-meter efforts in an outdoor velodrome, with four different handlebar heights, calculating both C_{DA} and oxygen consumption to determine aerodynamic-physiological economy.

This study confirmed that Notio is a reliable method for detecting C_{DA} differences in outdoor environments, with an inter-effort CV of 1.54% (approximately 4 W), with ranges between 0.02% and 6.57%. The typical error for C_{DA} was 0.0066 (0.0054–0.0085) m^2 , representing a trivial effect size. This value is slightly higher than the 0.002 m^2 detection threshold reported by Kordi et al. (2021) under indoor velodrome conditions.

Recently, new devices such as Aerosensor (Aerosensor Tech, Cambridge, UK) and GiBLI G10 (GiBLI Tech Inc., Barnstaple, UK) have emerged, expanding the commercially available options for aerosensors for aerodynamic assessment in the field. Aerosensor introduced some innovations, including its design inspired by Kiel probes used in Formula 1, which, according to the manufacturer, offers an accuracy of $\pm 1.5\%$ outdoors and $\pm 1\%$ indoors, with yaw angles of up to 50° . One of its main advantages is the supposed elimination of the need for a calibration protocol, which significantly simplifies its use. On the other hand, the GiBLI G10 device features a patented Pitot tube design that, according to the manufacturer, is capable of measuring wind direction with an accuracy of $\pm 0.5^\circ$, validated in

THEORETICAL BACKGROUND

a wind tunnel for yaw angles of up to 30° . To date, none of these devices has been subjected to independent scientific validations.

RATIONALE FOR THE THESIS

In cycling, aerodynamic resistance constitutes the main limiting factor at high speeds. As Barry et al. (2014) point out, more than 90% of the total power required at 50 km/h is used to overcome this air resistance. Knowing how and with what magnitude aerodynamic resistance acts allows taking the necessary measures to optimize performance (Debraux et al., 2011).

Among the methods available to evaluate aerodynamic resistance in cycling, the wind tunnel is considered the reference standard, a reliable and reproducible method, however, with limited accessibility due to its high cost (Brownlie, 2019). Additionally, the conditions simulated in a wind tunnel do not exactly replicate those experienced by a cyclist in a velodrome or on the road (Malizia & Blocken, 2020). Other methods such as CFD are also inaccessible for many athletes, not only due to the high economic cost, but also due to the need for specialized technical personnel for their application and interpretation.

Field tests, such as deceleration tests or constant speed tests have gained popularity as an alternative. These methods use formulas based on the principle of energy conservation, combining variables measured by different sensors with fixed estimated values reported in the scientific literature (Malizia & Blocken, 2020). However, these methods present significant challenges, particularly regarding wind measurement. The calculation of C_{DA} in field tests is based on mathematical models that, in many cases, ignore wind speed or use data from nearby weather stations, assuming zero or constant velocity. This simplification can introduce errors due to real wind fluctuations (Millour et al., 2022; Martin et al., 2006a).

In this context, devices such as Notio (Argon 18; Montreal, Canada) have emerged, integrating various sensors, including a Pitot-static tube to measure dynamic pressure and calculate the real wind speed that the cyclist faces. Despite their potential, the precision and reliability of these devices in measuring wind speed and calculating C_{DA} has been debated in the scientific literature, with studies showing varied results (Kordi et al., 2021; Valenzuela et al., 2020; Van Erp et al., 2021).

This research responds to the need to address several methodological questions that remain unresolved. First there is a noticeable lack of research

that explicitly looks at the validity and dependability of devices based on Pitot-static tubes in controlled settings like wind tunnels where their capabilities can be more precisely assessed under various wind angles and speeds. Prior to moving forward with more intricate field assessments, a controlled validation must be established.

Second, although these devices have been partially evaluated, few studies have directly analyzed their sensitivity to detect position changes in aerodynamic assessment protocols with professional cyclists. This validation is crucial to determine their practical usefulness in optimizing position and equipment in high-level cyclists.

Finally, it is unknown whether the C_{DA} values calculated by different methods are consistent between indoor and outdoor environments. This aspect is especially relevant since, although tests in wind tunnels or indoor velodromes can offer greater precision by minimizing the influence of wind (Dyer & Disley, 2018), most cyclists do not have access to these types of facility.

This doctoral thesis addresses these gaps by providing evidence on the validity, reliability, and practical application of aerosensors for aerodynamic assessment in cycling. The results have direct implications for athletes, coaches, and sports scientists, offering information on the real capabilities and limitations of this technology for the optimization of aerodynamic performance.

AIMS

General objective

To evaluate the validity, reliability, and practical application of Notio aerosensor in the calculation of C_{DA} in cycling, determining its usefulness as an alternative tool for aerodynamic optimization in cycling.

Specific objectives

- 1- To determine the validity and reliability of the C_{DA} calculated by Notio in comparison with the VE and Martin mathematical models, assessing its capacity to detect changes in different positions in professional cyclists in an indoor velodrome (Manuscript 1).
- 2- To evaluate the accuracy and reliability of Notio wind speed measurements in comparison with an HWA under controlled conditions in a wind tunnel, at different speed ranges and yaw angles (Manuscript 2).
- 3- To analyze the consistency of the C_{DA} values calculated by Notio and by the Martin mathematical model between indoor and outdoor environments, determining whether they provide equivalent results regardless of the test setting (Manuscript 3).
- 4- To evaluate the sensitivity of Notio and the Martin mathematical model to detect aerodynamic changes derived from different configurations both in indoor and outdoor conditions, determining their practical usefulness for selecting the most aerodynamic equipment (Manuscript 3).
- 5- Additionally, to establish methodological recommendations for the correct use of aerosensors in aerodynamic assessment in cycling, identifying their practical limitations (Manuscripts 1, 2 and 3).

METHODOLOGY

This doctoral thesis adopted a complementary methodological approach, structured in three studies to evaluate different aspects of the Notio aerosensor as a tool for calculating C_{DA} in cycling.

The first study focused on analyzing the validity and reliability of C_{DA} calculated by Notio in comparison with two mathematical models of VE and Martin. Seventeen professional cyclists (63.5 ± 8.1 kg, height: 175 ± 9 cm) voluntarily participated in the study.

Participants completed three series of 15 laps in a 250-meter indoor velodrome with concrete surface (Tafalla, Navarra, Spain), each with a different position: Baseline (B), Change 1 (C1), and Change 2 (C2). Each test series was preceded by 12 additional laps to calibrate the Notio device according to the manufacturer's instructions, plus 2 flying laps to reach the target speed and position. The bicycles were equipped with Power2max power meters (Saxonar GmbH, Walhufen, Germany) calibrated to zero before each test.

Weather conditions were recorded using the Notio device (temperature: $20^{\circ}\text{C} \pm 2.6$, humidity: $51.9 \pm 4\%$, atmospheric pressure: 1193 ± 11 hPa). The C_{rr} was set at 0.0025 for the three methods, according to previous research on concrete velodrome surfaces (Martin et al., 2006a). The transmission system efficiency was set at 97.7%, and the height of the center of mass was considered as the distance between the top of the saddle and the ground (Martin et al., 2006a).

C_{DA} was calculated using the three methods (Notio, VE, and Martin) and statistical analyses were performed using a spreadsheet and SPSS software (SPSS 25.0, Inc., Chicago, IL). A repeated measures ANOVA was performed to determine significant differences in speed and power between the three positions, and a second repeated measures ANOVA to examine the differences in C_{DA} between the methods for each position change.

With RStudio software (Version 1.4.1103) Bland-Altman plots and ICC analysis were used to assess the degree of agreement. The partial eta squared (η^2) was used to analyze the magnitude of the differences values of 0.01 0.06 and 0.14 were deemed small moderate and large respectively (Cohen 1977). The following criteria were used to interpret the ICC: low 0.80

METHODOLOGY

moderate 0.80–0.90 and high 0.90 (Koo and Li 2016). The limits of agreement (LoA) were presented as $\text{bias} \pm 1.96 \times \text{SD}$. Additionally, the differences between the C_DA results for each method between position changes were calculated, as well as the Pearson correlation coefficients (*r*) of these C_DA differences, and the Typical Error of Measurement (TEM). The *r* values of <0.1, 0.1–0.39, 0.4–0.69, 0.7–0.89, 0.9, and 1 were considered insignificant, weak, moderate, strong, and very strong, respectively (Schober et al., 2018). Finally, a linear regression was performed to determine the predictive capacity of the different measurement systems with respect to the others.

The second study evaluated the validity and reliability of wind speed calculated by Notio in comparison with an HWA. Sixty 30-second recordings were made in a closed-circuit wind tunnel (European University of Madrid, Spain), covering four different fan powers corresponding to mean wind speeds of 29.52 ± 0.29 km/h with 21% power, 39.59 ± 0.25 km/h with 28%, 50.42 ± 0.23 km/h with 37%, and 60.45 ± 0.29 km/h with 44%. Additionally, five different yaw angles were evaluated (0°, 5°, 10°, 15°, and 20°), using a protractor to adjust the orientation of Notio with respect to the airflow.

The HWA used was a Kanomax Anemomaster™ 6036-CE model (Andover, MA, USA), calibrated annually with a precision of $\pm 1\%$. Notio was fixed to a metal support at the base of the high-speed test section. Both devices were positioned centered with respect to the side walls, with a separation of 30 cm between them to avoid interference, with a blockage ratio of less than 0.2%. A Notio calibration process was carried out based on the reference value provided by the HWA at a speed of ≈ 30 km/h and a yaw angle of 0°.

Statistical analyses were performed with Jamovi statistical software (v2.4), setting the significance alpha at 0.05 with Bonferroni correction. The normality and variance of each variable were verified in each of the tests that required it. A repeated measures ANOVA was performed to study the validity of Notio and calibrated Notio (Notio_C) wind speed versus HWA.

Post hoc comparisons of means were analyzed to find differences between Notio_C and HWA wind speed for each speed group and yaw angle. The absolute mean differences (MD) and their 95% confidence

intervals (CI95), and the significance value (p) were reported, as well as Cohen's d as a measure of effect size (ES) and its CI95. The agreement between Notio_C and HWA was determined using a Bland-Altman plot with LoA presented as bias of $\pm 1.96 \times \text{SD}$ (Stöckl et al., 2004). The proportional bias line was plotted using a linear regression of the differences between the methods on the average of the measurements, as well as its confidence interval (Datta, 2017).

Absolute reliability for Notio_C and HWA was reported using the standard error of measurement (SEM) and its CI95 (standard error of measurement at 95% confidence [SEM95]). To measure relative reliability, the CV expressed as a percentage of the SEM (CV%), the ICC, and its CI95 were used. The ICC and its CI95 were calculated based on the mean score ($k = 3$), absolute agreement, and the two-way random effects model (Koo & Li, 2016).

The third study analyzed the consistency of C_DA data between indoor and outdoor environments and evaluated the sensitivity to detect aerodynamic changes with different equipment. Twelve trained cyclists (10 men and 2 women; age: 30 ± 7 years; weight: 71.5 ± 7.3 kg; height: 179.4 ± 5.3 cm) voluntarily participated. The inclusion criteria required previous experience in time trial competitions and riding in a velodrome.

Four different configurations were evaluated. The first was the baseline (Basal), which included a time trial bicycle, road helmet, two-piece equipment, and 50 mm wheels. The other three configurations modified only the component indicated by their name. In the "Wheels" configuration, a lenticular rear wheel and an 88 mm front wheel were used, in the "Helmet" configuration an aerodynamic time trial helmet was used, and in the "Skinsuit" configuration a time trial skin suit was used. The tests were carried out on a level straight road outside (coordinates 38.939191 and -0.480781) and in a 250-meter indoor velodrome (Luis Puig Valencia Spain).

The average weather conditions indoors were 22.2 ± 0.3 °C temperature, $56.5 \pm 4\%$ humidity, 1023.9 ± 6.9 mbar atmospheric pressure, and 1.201 ± 0.007 kg/m³ air density, while outdoors they were 22.9 ± 5.0 °C, $35.8 \pm 15.4\%$, 1023.5 ± 5.4 mbar, and 1.199 ± 0.022 kg/m³ respectively. Each cyclist performed 4 attempts with each configuration, completing a total of 32 segments of 1500m, 16 in each environment. The bicycles were equipped

METHODOLOGY

with a calibrated Assioma Duo pedal power meter (Favero Electronics, Italy), validated in previous studies, and a Sigma 20502 magnetic speedometer (Sigma Sport, Germany) linked to the Notio device. A portable weather station (Weathermeter, Weatherflow, USA) was used to measure environmental conditions.

The transmission efficiency was set at 97.7% and the C_{rr} at 0.0032 according to data published on the "Bicycle Rolling Resistance" website (<https://www.bicyclerollingresistance.com>) for the mounted tires. C_{DA} was calculated using the Notio device and Martin's mathematical model. All power and speed data were reviewed for outliers using the interquartile range (IQR) method.

Using G*Power version 3.1.9.7 an a priori power analysis was carried out to establish the bare minimum of the sample size (Faul et al., 2007) showed that with a significance criterion $\alpha = .05$ required a size of $N = 12$ to attain 80 % power. The Shapiro-Wilk test and Q-Q (quantile-quantile) plots were used to confirm normality. Normality was verified using the Shapiro-Wilk test and Q-Q (quantile-quantile) plots. A repeated measures ANOVA was performed to analyze the within-subject effects for the method-environment interaction, followed by post hoc comparisons adjusted using the Holm method, with the significance level set at $\alpha = 0.05$. The magnitude of the differences was analyzed using the MD and the standardized mean differences (Cohen's d , reported as effect size [ES]).

The agreement between environments for each method was determined using Bland-Altman plots, with LoA presented as bias $\pm 1.96 \times SD$. Absolute reliability was reported using the SEM, calculated as $\sqrt{MSE}$ where MSE is the mean square error term from the repeated measures ANOVA (Weir & Vincent, 2020). The SEM95 was calculated, which represents the 95% confidence interval for the standard error of measurement, using $SEM \times 1.96$. For relative reliability, the CV%, the ICC, and their confidence intervals were used. The ICC estimates and their CI95% were based on the mean score ($k = 4$), absolute agreement, and the two-way random effects model. The within-subject standard deviation (s_w) was also reported for each configuration as a measure of repeatability (Bland & Altman, 1996). All statistical analyses were performed using the open-source software JASP (JASP Team, 2024).

RESULTS

The first study showed that Notio presented a high correlation with other validated mathematical models, with an ICC of 0.820 (95% CI: 0.685–0.898; $p < .001$) relative to VE and an ICC of 0.832 (95% CI: 0.705–0.904; $p < .001$) relative to Martin.

C_{DA} values calculated by Notio were slightly lower than those calculated by the mathematical models, with a bias of $-0.004 \pm 0.017 \text{ m}^2$ compared to VE and $-0.009 \pm 0.016 \text{ m}^2$ compared to Martin. Bland-Altman analysis revealed a non-systematic proportional (non-constant) bias between Notio and both mathematical models, with a positive trend in the differences as the magnitude of the measured variable increased. Regarding the ability to detect changes between positions, Notio showed a moderate correlation with both mathematical models ($r = 0.411$, $p = .003$ for Notio-VE; $r = 0.409$, $p = .003$ for Notio-Martin), while the correlation between the mathematical models was perfect ($r = 1$, $p < .01$).

None of the three methods showed sufficient sensitivity to detect statistically significant changes between positions ($p > .05$), indicating a limitation in their ability to detect small aerodynamic improvements in professional cyclists when the proposed changes are small.

In the second study, the initial wind speed measurements performed by Notio showed significant differences compared to the HWA, being 6.44% higher. After the calibration process recommended by the manufacturer, these differences were reduced to 0.76%, being non-significant ($p = 0.117$, $ES = -0.63$, $MD = -0.34$, 95% CI: -0.76 to 0.08). The analysis by speed groups showed that calibrated Notio had similar accuracy to the HWA in the ≈ 30 , ≈ 40 , and $\approx 50 \text{ km/h}$ ranges, with non-significant differences. However, significant differences were observed in the $\approx 60 \text{ km/h}$ group ($p < 0.001$, $ES = -3.52$, $MD = -1.90$, 95% CI: -2.72 to -1.07), suggesting the need to calibrate the device at a speed close to the evaluation conditions.

Regarding yaw angles, no significant differences were found between calibrated Notio and the HWA in any of the groups (0° , 5° , 10° , 15° , and 20°), confirming the device's ability to maintain its accuracy even with crosswind. The Bland-Altman analysis showed a low bias of -0.342 km/h with LoA from -2.687 to 2.003 km/h , and a non-constant systematic bias

RESULTS

with a negative trend in the differences as the magnitude of the measured variable increased, suggesting that discrepancies between measurements tend to widen at higher speeds. The reliability analysis showed that Notio presents good values, although lower than those of the HWA, with a CV% of 1.02 and an SEM of ± 0.455 km/h, compared to a CV% of 0.59 and an SEM of ± 0.261 km/h for the HWA.

The third study found that C_{DA} was lower in the outdoor environment (Notio = 0.251 m^2 ; Martin = 0.242 m^2) compared to indoor (Notio = 0.252 m^2 ; Martin = 0.248 m^2). The comparison of C_{DA} values between indoor and outdoor environments showed significant differences for the Martin method ($p < 0.001$, $ES = 0.477$, $MD = 0.006 \text{ m}^2$, 95% CI: 0.002 to 0.010), with higher indoor values (2.4%). In contrast, Notio showed no significant differences between environments ($p = 0.569$, $ES = 0.058$, $MD = 0.001 \text{ m}^2$, 95% CI: -0.003 to 0.005), demonstrating its consistency regardless of the test environment.

Bland-Altman analysis showed a low bias for Notio (0.001) with a standard deviation of ± 0.005 , while Martin showed a slightly higher bias (0.006) with a standard deviation of ± 0.009 . The limits of agreement for Notio (lower = -0.010, upper = 0.011) and Martin (lower = -0.011, upper = 0.023) indicate that most differences fall within these ranges, suggesting acceptable agreement between measurements.

Regarding absolute reliability, Notio presented an SEM of $\pm 0.004 \text{ m}^2$ indoors and $\pm 0.003 \text{ m}^2$ outdoors, and an SEM95 of $\pm 0.008 \text{ m}^2$ indoors and $\pm 0.006 \text{ m}^2$ outdoors; Martin, on the other hand, showed an SEM of $\pm 0.005 \text{ m}^2$ indoors and $\pm 0.006 \text{ m}^2$ outdoors, and an SEM95 of $\pm 0.009 \text{ m}^2$ indoors and $\pm 0.012 \text{ m}^2$ outdoors.

DISCUSSION

This doctoral thesis provides an evaluation of the validity, reliability, and practical application of the Notio device for calculating C_{DA} in cycling. The results obtained through three complementary studies allow establishing relevant conclusions about its usefulness as an alternative tool to traditional methods.

The validity analysis of C_{DA} calculated by Notio versus the VE and Martin mathematical models demonstrated a high correlation, with ICCs above 0.8, indicating a good level of agreement between methods. Despite this agreement, none of the three methods was sufficiently sensitive to detect position changes, probably because the participants, all professional cyclists, already had an optimized initial position. This result coincides with the findings of Valenzuela et al. (2020), who also reported a good correlation between Notio and other validated methods. However, our data revealed a novel aspect. Although the absolute C_{DA} values are comparable, the direction of the changes detected between different positions was different between Notio and the mathematical models. This discrepancy has important practical implications, as it could lead to different recommendations on the ideal position of the cyclist. These results, along with the observations of Valenzuela et al. (2020), reinforce the idea that Notio has limitations in detecting small aerodynamic changes.

Regarding absolute C_{DA} values, those calculated by Notio in our study were slightly lower than those obtained through mathematical models, 2% less than VE and 4% less than Martin, which contrasts with the data published by Valenzuela et al. (2020), where Notio results were 1.6% higher than those of the Martin model. This difference could be due to several factors, such as the possible discrepancy between the measurements of the Pitot tubes of different Notio units, as reproducibility between devices has not yet been evaluated. Another factor could be that in Valenzuela et al. (2020), Notio and Martin used different sources to incorporate temperature, humidity, and pressure data, whereas in our study, both systems used the same source for these environmental parameters.

The higher C_{DA} result shown by the Martin model can be explained by the variable that this model incorporates to consider the dynamics of track

DISCUSSION

cycling, which corrects downward the speed measured by the speedometer on the wheel (Martin et al., 2006). This suggests that both Notio and VE could provide C_{DA} values lower than the real ones under specific track cycling conditions.

Differences found between the baseline position and C2 in the three systems were 0.009 m^2 , with the largest change recorded of 0.011 m^2 , measured by Notio, between the baseline position and C1. Although we did not find statistical significance between position changes, the improvements in C_{DA} according to our calculations could mean an increase in speed of 0.55 km/h , which would translate into a time improvement of approximately 1 minute in a 40 km time trial, or a power saving of between 10 and 11 watts at constant speed.

Validation of wind speed calculated by Notio under controlled wind tunnel conditions provides fundamental information about the accuracy of this key variable in the calculation of C_{DA} . After the calibration recommended by the manufacturer, the differences compared to the HWA were reduced to 0.76%, demonstrating that Notio can measure wind speed with good accuracy in the usual speed ranges in cycling ($\approx 30\text{-}50 \text{ km/h}$). Before calibration, Notio measured speeds 6.44% higher than the HWA, with an absolute difference of 2.90 km/h , confirming the need for the calibration process to ensure the validity of the measurement. This result contrasts with that reported by Van Erp et al. (2021), who found difficulties in the accuracy of wind speed with different yaw angles. Our data indicate that Notio maintains its accuracy even with angles up to 20° , which is consistent with the aerodynamic characteristics of hemispherical head Pitot tubes described by Walchner (1939), who reported errors of only 1% at angles up to 15° and less than 2% for 20° . Other authors have also shown pressure coefficients close to 1 for angles up to 20° , supporting our findings (Beck et al., 2010). Additionally, in competition due to high speeds, it is estimated that only 5% of the wind could exceed 20° of yaw (Cooper, 2003), with accuracy at extreme yaw angles being less critical.

The decrease in precision observed at higher speeds ($\approx 60 \text{ km/h}$) represents a significant limitation. Considering that many professional time trial tests are developed at speeds that, added to the headwind, can exceed this speed, caution is required when interpreting results under these

conditions. This finding suggests the need to calibrate the device at speeds close to those of the aerodynamic evaluation, a phenomenon also observed by Van Erp et al. (2021), who found that the error increased at speeds lower or higher than the calibration speed. In their study, Notio showed a better response in this aspect than Aeropod, another aerosensor model. Regarding the reliability analysis, Notio showed good values with a coefficient of variation (CV%) of 1.02 and a standard error of measurement (SEM) of ± 0.455 km/h, although these results were approximately 50% lower than those of the HWA (CV% = 0.59, SEM of ± 0.261 km/h). In aerodynamic evaluations, reliability is usually a preferable factor even over absolute precision, as the usual objective is to compare configurations, and not so much to know the real and precise value of the C_{DA} .

Regarding the consistency of measurements between indoor and outdoor environments, Notio revealed an advantage over the Martin model. While Martin showed significant differences (2.4% higher in indoor, $p < 0.001$), Notio showed consistent values regardless of the test environment. This characteristic is particularly valuable considering that, although velodrome evaluations offer more controlled conditions, not all cyclists can have access to indoor track facilities, and outdoor riding is more representative of reality for most cycling events. Notio's ability to provide comparable measurements in both environments facilitates the use of this tool. This consistency is possibly due to the ability of the Pitot-static tube to correctly measure the dynamic pressure experienced by the cyclist in real time, providing more precise data on the actual wind faced by the cyclist.

However, the most relevant finding from a practical perspective is related to the sensitivity of the evaluated methods. None of them, including Notio, demonstrated the ability to reliably detect small aerodynamic changes, as the SEM95 exceeded the observed differences between different equipment configurations. This result has important implications for the practical application of these systems in aerodynamic optimization in elite cyclists. A C_{DA} change of only 0.001 m^2 can represent a difference of approximately 11 seconds in a 40 km time trial at competition speeds, a time difference that can be determinant for the final result. The inability of these techniques to accurately identify changes of this size limits their applicability in high-performance cycling where even small gains can make

DISCUSSION

all the difference. To put this magnitude in perspective Tadej Pogačar finished a 40.6 km time trial at an average speed of 47.1 km/h during the 2024 Giro d'Italia. Based on our calculations using the Martin formula a 0.001 m² improvement in the C_DA could yield an 11-second advantage which could decide the outcome of the general classification or the stage victory.

Various factors contribute to this limitation in terms of sensitivity. First, measurements made in a velodrome present technical limitations, such as the need to maintain a constant position while interacting with the variable geometry of the track. Fitzgerald et al. (2021) emphasize that this requires constant adjustments in inclination, speed, cadence, and power, which could compromise the reliability of repeated measurements, masking small aerodynamic improvements. In outdoor environments, accurately incorporating wind into the C_DA calculation equation represents an additional challenge. Added to this is the difficulty in exactly replicating the same body position between attempts, which introduces a source of variability. Even under controlled wind tunnel conditions, it has been shown that small changes in the position of the upper body, especially in head height and torso angle, can have a significant impact on C_DA, as pointed out by Crouch et al. (2021).

Power meter error is another important factor. Rielves et al. (2021) reported an absolute reliability of ± 6.4 W for the same model used in this research, which according to calculations based on the Martin formula could translate into a C_DA variability of approximately ± 0.006 m². Other studies on validation of power meters used in cycling report CVs between 0.4 and 3% (Bertucci et al., 2005; Maier et al., 2017; Pallarés & Lillo-Bevia, 2018), which can translate into power variabilities close to the one mentioned. This magnitude of instrumental error alone exceeds many of the aerodynamic changes that are intended to be detected in an aerodynamic evaluation protocol. In addition, air density is another factor that influences C_DA calculations. In our outdoor measurements, we observed changes in air density of up to 3% throughout the protocol with the same cyclist, mainly due to temperature variations. Underwood (2012) reported an uncertainty of 0.4% in the calculation of air density under specific conditions (20°C, 1000hPa), which according to our calculations based on the Martin formula

could translate into an approximate error of 0.001 m^2 in the calculation of C_{DA} .

Our results can be compared with those of Kordi et al. (2021), who analyzed the performance of Notio in an indoor velodrome. Their range of s_w ($0.001\text{-}0.003 \text{ m}^2$) was slightly lower than that observed in our study ($0.002\text{-}0.005 \text{ m}^2$). This difference could be attributed to their sample of elite track cyclists, who would presumably be more consistent in position replication.

On the other hand, Valenzuela et al. (2020) reported a s_w of 0.015 m^2 , three times higher than our highest average value and five times higher than the maximum value reported by Kordi et al. (2021). This high variability shows a limitation in the system's ability to detect real C_{DA} changes between different configurations. The fact of using in their study a CycleOps PPI power meter with a CV between 1.6 and 3.7% according to Pallarés & Lillo-Bevia (2018), could have contributed to this greater variability. In addition, their sample of trained, but not elite cyclists probably made it difficult to replicate positions between attempts, especially considering that they evaluated three configurations that included an upright position, which allows greater joint mobility in elbows and hip.

Beyond the type of position adopted, outdoor conditions pose an added difficulty in ensuring the repeatability of C_{DA} measurements. In this sense, Merkes et al. (2019) observed a high variability in field tests performed in different cyclist sprint positions. The authors reported high CVs for the same position, between 9.1% and 16.0%. Even after a week of training and a familiarization session they noted that obtaining accurate C_{DA} measurements in sprint positions was still difficult. They ascribed this variability to the incapacity of cyclists to replicate consistent positions between attempts as well as the inherent variability of outdoor conditions.

The fact that different studies have different results emphasizes how crucial it is to take into account variables like the kind of power meter being used the experience of cyclists and the particular aerodynamic evaluation methodology when interpreting C_{DA} data.

LIMITATIONS

This work presents several limitations that should be considered when interpreting the results.

In the validation study with professional cyclists, the postural modifications performed were limited by equipment restrictions due to commercial contracts and UCI regulations, which may have conditioned the magnitude of the aerodynamic changes that could be evaluated. Additionally, although the sample consisted of professional cyclists, capable of maintaining a high level of consistency in posture, the inherent variability in maintaining an exact position during high intensity pedaling introduces an unquantified error factor.

Measurements in the wind tunnel study were conducted without the cyclist and bicycle present. This gives insight into how the Pitot-static sensor behaves in conditions of uniform flow but it does not account for the potential disturbances that the cyclist-bicycle system may cause in real-world scenarios. The temperature humidity and atmospheric pressure on the other hand were essentially constant throughout the experiment making it impossible to assess how these variations affected the precision of the measurements. These controlled conditions differ from the dynamic environments where Notio is used in practice, where variable environmental factors could affect its performance. Moreover, the device was calibrated at a single reference speed, which may not ensure the validity of the measurements at speeds different from the calibration speed. There is also no available information on the formula that Notio uses to calculate C_{DA} , which prevents quantifying the effect of wind speed error on the C_{DA} calculation.

In the comparative study between indoor and outdoor environments, the wind measurement at a single point of the outdoor course represents a simplification that may not adequately reflect the conditions experienced by the cyclist. During the tests, we were unable to measure constant wind in the outdoor environment, only some gusts at specific moments, and therefore we did not incorporate wind into the C_{DA} calculation using the Martin method. Furthermore, the same C_{rr} value was used for both environments, despite the different rolling surfaces between the concrete velodrome and

LIMITATIONS

the asphalt road, which could have influenced the comparison of the absolute C_{DA} values.

A general limitation is the use of a single Notio device, which does not allow the evaluation of variability between different units of the same model.

FUTURE RESEARCH

The results and limitations of this doctoral thesis suggest various lines of future research.

It is convenient to carry out studies on the comparison between different units of Notio, as the degree of variability between different devices of this same model is currently unknown. Determining whether all devices provide equivalent measurements is fundamental for comparing results between different studies. In addition, it would be necessary to develop research focused on evaluating the reliability and precision of each of the sensors integrated in the Notio aerosensor to better understand the sources of variability in the calculation of C_{DA} .

On the other hand, more studies on the validity and reliability of Notio in the wind tunnel with the presence of the cyclist and bicycle are necessary, to determine the influence of flow disturbances generated by the assembly on the precision of measurements. Similarly, the behavior of the aerosensor in different atmospheric conditions should be studied to establish its sensitivity to these variations.

Considering the limitations in sensitivity, future research could focus on the development of methodologies that minimize sources of error, especially in power measurement and in the ability of cyclists to replicate consistent body positions during repeated tests.

CONCLUSIONS

Notio shows a high correlation with other validated mathematical models in the calculation of absolute C_{DA} . However, the direction of changes detected between different positions differs between Notio and mathematical models, which could translate into different recommendations about the optimal position in elite cyclists (Aim 1).

Regarding the calculation of wind speed, the Notio aerosensor allows obtaining precise records in a wide range of speeds and yaw angles after a calibration process in a wind tunnel. The data show that Notio calibrated at a speed close to that of use allows a reliable and precise calculation, although its reliability was lower than that of an HWA. However, due to the influence of wind speed on aerodynamic resistance, small errors in this measurement could translate into considerable C_{DA} values, which could significantly affect its practical utility (Aim 2).

In assessing the consistency in the calculation of C_{DA} between indoor and outdoor environments, Notio shows comparable results, without significant differences between both. In contrast, the Martin method presents significantly higher C_{DA} values indoors (Aim 3). However, neither of the two methods could detect statistically significant differences between the different equipment configurations tested (Aim 4).

For the correct use of aerosensors in cycling, it is recommended to consider that although Notio shows high correlation with validated mathematical models in calculating absolute C_{DA} , the direction of changes detected between different positions may differ, which could result in different recommendations about optimal position; calibrate the device at speeds similar to those of the intended evaluation test; evaluate the reliability of the power meter used before testing, contextualizing in practical terms how this error impacts the reliability of C_{DA} calculation; and conduct multiple trials for each tested configuration reporting average values along with SEM95 for a more accurate interpretation of real aerodynamic changes (Aim 5).

In conclusion, although Notio represents a significant advance in terms of the accessibility of aerodynamic evaluations in cycling, and provides valid measurements of C_{DA} , its sensitivity, like that of the evaluated

CONCLUSIONS

mathematical models, is insufficient to detect small aerodynamic changes that could be decisive in competition.

PRACTICAL APPLICATIONS

The results of this research allow establishing various recommendations for the practical application of these methods by cyclists, coaches, and sports scientists.

First, Notio represents a valid and accessible alternative to traditional methods for calculating absolute C_{DA} , showing a high correlation with validated mathematical models. However extrapolating results directly between methods is not advised due to the differences in change direction that have been observed. We advise calibrating the device at speeds that are similar to those that will be used for the evaluation in order to obtain accurate readings especially since accuracy drastically declines at speeds higher than 50 km/h after calibrating at about 30 km/h. Due to the limited sensitivity of the evaluated methods, it is recommended to perform multiple measurements for each tested configuration, reporting the average C_{DA} values along with the s_w . This approach facilitates predictions and comparisons based on ranges, providing a more realistic representation of the inherent variability in aerodynamic measurements under field conditions.

In the interpretation of results, it is fundamental to evaluate the practical significance of detected C_{DA} changes in terms of time or power savings for a specific distance and speed of the target competition. This approach will allow adequately contextualizing the relevance of aerodynamic changes.

Finally, it is recommended to perform a prior evaluation of the reliability of the power meter that will be used in aerodynamic tests. This analysis will allow knowing a priori the minimum sensitivity achievable in the determination of C_{DA} , avoiding investing time and resources in trying to detect aerodynamic changes below this threshold of instrumental precision.

The identified limitations should not discourage the adoption of these field aerodynamic assessment methods. Understanding the sources of error can help improve test conditions and establish a clearer range of detectable C_{DA} changes, optimizing time and resources while recognizing their limitations.

RESUMEN (SPANISH SUMMARY)

Introducción General

La resistencia aerodinámica surge como un elemento clave que limita el rendimiento en ciclismo a velocidades elevadas. Esta resistencia constituye hasta el 90% de la resistencia total que se opone al avance a velocidades de 30 km/h afectando de manera significativa a la eficiencia energética y al rendimiento final del ciclista (Gibertini et al., 2011). Es crucial mejorar el rendimiento aerodinámico en el ciclismo moderno donde a menudo la victoria se decide por pocos segundos. Barry et al. (2015) evidenciaron que mejorar la posición puede traducirse en una reducción del 16% en la resistencia aerodinámica destacando la relevancia de los ajustes biomecánicos teniendo en cuenta que el cuerpo del ciclista constituye cerca del 79% del C_{DA} (Chi et al., 2020).

Fuerzas externas

La investigación sistemática de las fuerzas que actúan sobre el ciclista y los métodos para su evaluación son áreas de estudio esenciales para optimizar el rendimiento. Dentro de estas fuerzas, la resistencia aerodinámica destaca por su peso relativo en la potencia generada a velocidades competitivas lo cual respalda el interés creciente por las tecnologías dedicadas a su estudio. En este contexto la validación de dispositivos como Notio, un aerosensor creado para calcular el C_{DA} en pruebas de campo, puede suponer un progreso importante en la optimización aerodinámica.

El rendimiento en el ciclismo está determinado por diversas fuerzas físicas que influyen de manera simultánea en el ciclista. Entender estas fuerzas resulta fundamental para mejorarlo. La fuerza aerodinámica, la resistencia a la rodadura, la fuerza gravitatoria y la fricción son las cuatro fuerzas que determinan la dinámica ciclista. La inercia por otra parte, a pesar de no ser una fuerza sino una característica de la materia, también se tiene en cuenta en el estudio de los cambios de velocidad (Glaskin, 2013).

Origen y evolución del estudio de la aerodinámica en ciclismo

La evolución tecnológica de la bicicleta, así como la popularización de las competiciones, favoreció alcanzar velocidades cada vez más altas donde la optimización aerodinámica resultaba fundamental. A finales del siglo XIX, esta resistencia ya se había identificado como la fuerza limitante predominante (Malizia y Blocken, 2020).

A lo largo de la historia, se han desarrollado varias técnicas para valorar la resistencia aerodinámica en el ciclismo, cada una con sus particularidades. Tradicionalmente el túnel de viento ha sido considerado como el método de referencia para las valoraciones aerodinámicas. Los primeros estudios experimentales llevados a cabo por Kawamura (1953, citado en Kyle, 1979) y Nonweiler (1956), sentaron las bases de esta metodología.

Posteriormente, el método de remolque desarrollado por Di Prampero et al. (1979), se presentó como una alternativa que implicaba remolcar ciclistas mediante un cable a velocidades constantes y registrar directamente la fuerza de tracción con un dinamómetro. Este método permite ensayos en situaciones reales, aunque introduce restricciones como la turbulencia producida por el vehículo remolcador.

En este mismo periodo se desarrolló el método de desaceleración, basado en la curva de velocidad-tiempo durante la desaceleración, capaz de determinar al mismo tiempo la resistencia aerodinámica y la de rodadura. Kyle y Burke (1984) realizaron varias investigaciones con diferentes variantes de este método.

Gracias al progreso tecnológico, y con la aparición de medidores de potencia fiables, surgieron modelos matemáticos fundamentados en potencia. En este contexto, Grappe et al., (1997) desarrollaron un método para calcular C_{DA} y C_{rr} a través de mediciones directas en condiciones de campo. Varios años más tarde, Martin et al. (1998, 2006a) enriquecieron este método al incorporar correcciones sistemáticas y desarrollar protocolos específicos para diferentes entornos.

Con este progreso, el método de Elevación Virtual (VE) establecido por Robert Chung en 2012, posibilitó la evaluación aerodinámica en varios contextos reales utilizando los datos de potencia, velocidad y aceleración para determinar perfiles de elevación virtual.

Simultáneamente, la dinámica de fluidos computacional (CFD) desde 2010 posibilitó la visualización de fenómenos de flujo alrededor del ciclista. Dentro de este campo, Defraeye et al. (2010a, 2010b) hicieron aportes significativos al comparar simulaciones CFD con mediciones reales.

Por otra parte, la velocimetría de imagen de partículas (PIV), posibilitó la visualización de estructuras vorticales y fenómenos transitorios. Con esta metodología Chabroux et al. (2010) explicaron el flujo vortical en estelas de cascos, mientras Terra et al. (2018) analizaron planos transversales detrás de maniqués a escala real.

Finalmente, los progresos tecnológicos en miniaturización de sensores, capacidad para procesar datos y sistemas de conectividad, han facilitado la

producción de dispositivos portátiles basados en tubos Pitot denominados aerosensores para la valoración aerodinámica en campo.

Estos dispositivos abordan diversos retos al proporcionar mediciones directas del viento relativo, automatizando la gestión de datos a través de programas de computación y mostrando valores de C_{DA} en tiempo real. Automatizar el proceso de datos suprime la necesidad de cálculos posteriores recortando el tiempo entre la recolección de datos y la interpretación de los resultados. Además, el monitoreo en tiempo real del C_{DA} durante la actividad facilita al ciclista feedback instantáneo acerca del impacto aerodinámico que surge de los cambios en la posición.

Los aerosensores incorporan varios sensores entre los que se incluye un tubo Pitot-estático para determinar la velocidad del viento al que se enfrenta el ciclista. A pesar de su potencial, la precisión y fiabilidad de estos aparatos para medir la velocidad del viento y calcular el C_{DA} ha generado discusiones en la literatura científica con investigaciones que presentan resultados diversos (Kordi et al., 2021; Valenzuela et al., 2020; Van Erp et al., 2021).

Esta investigación trata diversos interrogantes respecto a la validación y uso práctico de los aerosensores en el ciclismo. Estos incluyen la ausencia de investigaciones que examinen específicamente la validez y fiabilidad de dispositivos basados en tubos Pitot-estáticos en entornos controlados como túneles de viento, la escasez de estudios que analicen directamente su sensibilidad para detectar cambios de posición en protocolos de evaluación aerodinámica con ciclistas profesionales y el desconocimiento sobre si los valores de C_{DA} calculados son consistentes entre entornos indoor y outdoor.

Objetivos

El trabajo de investigación tiene como objetivo general evaluar la validez, fiabilidad y aplicación práctica del aerosensor Notio en el cálculo del C_{DA} en ciclismo, determinando su utilidad como herramienta alternativa para la optimización aerodinámica.

De manera específica, determina la validez y fiabilidad del C_{DA} calculado por Notio en comparación con los modelos matemáticos de VE y Martin, evaluando su capacidad para detectar cambios en diferentes posiciones en ciclistas profesionales en un velódromo cubierto.

Asimismo, busca evaluar la precisión y fiabilidad de las mediciones de velocidad del viento de Notio en comparación con un HWA bajo condiciones controladas en un túnel de viento, en diferentes rangos de velocidad y ángulos de guiñada.

Otro de los objetivos específicos consiste en analizar la consistencia de los valores de C_{DA} calculados por Notio y por el modelo matemático de Martin entre entornos interiores y exteriores, determinando si proporcionan

resultados equivalentes independientemente del entorno de prueba. También se pretende evaluar la sensibilidad de Notio y del modelo matemático de Martin para detectar cambios aerodinámicos derivados de diferentes configuraciones tanto en condiciones de interior como de exterior, determinando su utilidad práctica para seleccionar el equipamiento más aerodinámico.

Finalmente, se busca establecer recomendaciones metodológicas para el uso correcto de aerosensores en la evaluación aerodinámica en ciclismo, identificando sus limitaciones prácticas.

Metodología

Para alcanzar estos objetivos, la tesis doctoral adoptó un enfoque metodológico complementario, estructurado en tres estudios que evaluaron diferentes aspectos del aerosensor Notio como herramienta para el cálculo del C_{DA} en ciclismo.

El primer estudio se centró en analizar la validez y fiabilidad del C_{DA} calculado por Notio en comparación con dos modelos matemáticos de VE y Martin. Participaron voluntariamente 17 ciclistas profesionales (63.5 ± 8.1 kg, altura: 175 ± 9 cm), completando tres series de 15 vueltas en un velódromo cubierto de 250 metros con superficie de hormigón (Tafalla, Navarra, España), cada una con una posición diferente: Línea Base (B), Cambio 1 (C1) y Cambio 2 (C2). Cada serie de pruebas fue precedida por 12 vueltas adicionales para calibrar el dispositivo Notio según las instrucciones del fabricante, más 2 vueltas lanzadas para alcanzar la velocidad y posición objetivo.

Las bicicletas estaban equipadas con potenciómetros Power2max (Saxonar GmbH, Walhufen, Alemania) calibrados a cero antes de cada prueba. Las condiciones meteorológicas se registraron mediante el dispositivo Notio (temperatura: $20^{\circ}\text{C} \pm 2.6$, humedad: $51.9 \pm 4\%$, presión atmosférica: 1193 ± 11 hPa). El C_{rr} se estableció en 0.0025 para los tres métodos, de acuerdo con investigaciones previas sobre superficies de hormigón en velódromo (Martin et al., 2006a). La eficiencia del sistema de transmisión se estableció en 97.7%, y la altura del centro de masa se consideró como la distancia entre la parte superior del sillín y el suelo (Martin et al., 2006a).

El C_{DA} se calculó utilizando los tres métodos (Notio, VE y Martin) y los análisis estadísticos se realizaron utilizando una hoja de cálculo y el software SPSS (SPSS 25.0, Inc., Chicago, IL). Para determinar diferencias en velocidad y potencia entre las tres posiciones se realizó un ANOVA de medidas repetidas. Un segundo ANOVA de medidas repetidas analizó las diferencias en C_{DA} entre los métodos en cada cambio de posición.

Evaluamos el grado de acuerdo con gráficos de Bland-Altman y ICC con el software RStudio (Versión 1.4.1103).

Por otra parte, el eta cuadrado parcial (η^2) se eligió para analizar la magnitud de las diferencias considerando los valores de 0.01, 0.06 y 0.14 como pequeños, moderados y grandes, respectivamente. Se utilizaron los siguientes criterios para interpretar el ICC: bajo 0.80, moderado 0.80-0.90 y alto 0.90 (Koo and Li 2016). Los límites de acuerdo (LoA) se presentaron como sesgo $\pm 1.96 \times \text{SD}$. Se calcularon también las diferencias entre los resultados de $C_D A$ para cada método entre cambios de posición, y los coeficientes de correlación de Pearson (r) de estas diferencias de $C_D A$, y el Error Típico de Medición (TEM). Los valores de r de <0.1 , $0.1-0.39$, $0.4-0.69$, $0.7-0.89$, 0.9 y 1 se consideraron insignificantes, débiles, moderados, fuertes y muy fuertes respectivamente (Schober et al., 2018). Por último, una regresión lineal determinó la capacidad predictiva de los diferentes sistemas de medición con respecto a los otros.

El segundo estudio evaluó la validez y fiabilidad de la velocidad del viento calculada por Notio en comparación con un HWA. Se realizaron sesenta registros de 30 segundos en un túnel de viento de circuito cerrado (Universidad Europea de Madrid, España), abarcando cuatro potencias diferentes del ventilador correspondientes a velocidades medias del viento de 29.52 ± 0.29 km/h con 21% de potencia, 39.59 ± 0.25 km/h con 28%, 50.42 ± 0.23 km/h con 37%, y 60.45 ± 0.29 km/h con 44%. Adicionalmente, se evaluaron cinco ángulos de guiñada diferentes (0° , 5° , 10° , 15° y 20°).

La orientación de Notio con respecto al flujo de aire se ajustó utilizando un transportador de ángulos. El HWA utilizado fue un modelo Kanomax Anemomaster™ 6036-CE (Andover, MA, USA), calibrado anualmente con una precisión de $\pm 1\%$. Notio se fijó a un soporte metálico en la base de la sección de prueba. Ambos dispositivos se colocaron centrados respecto a las paredes laterales con una separación de 30 cm entre ellos para evitar interferencias. La relación de bloqueo fue inferior al 0.2%. Se llevó a cabo un proceso de calibración de Notio basado en el valor de referencia proporcionado por el HWA a una velocidad de ≈ 30 km/h y un ángulo de guiñada de 0° .

Se utilizó el software estadístico Jamovi (v2.4) para realizar los análisis estadísticos, estableciendo el alfa de significación en 0.05 con corrección de Bonferroni. Se verificaron la normalidad y la varianza de cada variable en cada una de las pruebas que lo requerían. Se realizó un ANOVA de medidas repetidas para estudiar la validez de la velocidad del viento de Notio y Notio calibrado (Notio_C) frente a HWA. Se analizaron comparaciones post hoc de medias para encontrar diferencias entre la velocidad del viento de

Notio_C y HWA para cada grupo de velocidad y ángulo de guiñada. Se informaron las diferencias medias absolutas (MD) y sus intervalos de confianza del 95% (IC95), y el valor de significación (p), así como la d de Cohen como medida del tamaño del efecto (ES) y su IC95.

El acuerdo entre Notio_C y HWA se determinó utilizando un gráfico de Bland-Altman con LoA presentados como sesgo de $\pm 1.96 \times \text{SD}$ (Stöckl et al., 2004). La línea de sesgo proporcional se trazó utilizando una regresión lineal de las diferencias entre los métodos sobre el promedio de las mediciones, así como su intervalo de confianza (Datta, 2017).

La fiabilidad absoluta para Notio_C y HWA se informó utilizando el error estándar de medición (SEM) y su IC95 (error estándar de medición al 95% de confianza [SEM95]). Para medir la fiabilidad relativa, se utilizaron el CV expresado como porcentaje del SEM (CV%), el ICC y su IC95. El ICC y su IC95 se calcularon basándose en la puntuación media ($k = 3$), acuerdo absoluto y el modelo de efectos aleatorios de dos vías (Koo & Li, 2016).

El tercer estudio analizó la consistencia de los datos de C_{DA} entre entornos interiores y exteriores, evaluando además la sensibilidad para detectar cambios aerodinámicos con diferente equipamiento. Doce ciclistas entrenados participaron voluntariamente (10 hombres y 2 mujeres; edad: 30 ± 7 años; peso: 71.5 ± 7.3 kg; altura: 179.4 ± 5.3 cm). Los criterios de inclusión requerían experiencia previa en competiciones de contrarreloj y en el velódromo.

Se evaluaron cuatro configuraciones diferentes. La primera fue la línea base (Basal), que incluía una bicicleta de contrarreloj, casco de carretera, ropa de dos piezas y ruedas de 50 mm. Las otras tres configuraciones modificaban solo el componente indicado por su nombre. En la configuración "Wheels" se utilizó una rueda lenticular trasera y una rueda delantera de 88 mm, en la "Helmet" se usó un casco aerodinámico, y en la "Skinsuit" se utilizó un traje de una pieza de contrarreloj.

Las pruebas se realizaron en una carretera recta y llana en el exterior (coordenadas 38.939191 y -0.480781) y en un velódromo cubierto de 250 metros (Luis Puig Valencia, España). Las condiciones meteorológicas promedio en interior fueron 22.2 ± 0.3 °C de temperatura, $56.5 \pm 4\%$ de humedad, 1023.9 ± 6.9 mbar de presión atmosférica y 1.201 ± 0.007 kg/m³ de densidad del aire, mientras que en exterior fueron 22.9 ± 5.0 °C, $35.8 \pm 15.4\%$, 1023.5 ± 5.4 mbar y 1.199 ± 0.022 kg/m³ respectivamente.

Cada ciclista realizó 4 intentos con cada configuración, completando un total de 32 segmentos de 1500m, 16 en cada entorno. Las bicicletas estaban equipadas con un potenciómetro de pedal Assioma Duo calibrado (Favero

Electronics, Italia), validado en estudios previos, y un velocímetro magnético Sigma 20502 (Sigma Sport, Alemania) vinculado al dispositivo Notio. Se utilizó una estación meteorológica portátil (Weathermeter, Weatherflow, USA) para medir las condiciones ambientales.

La eficiencia de transmisión se estableció en 97.7% y el C_{tr} en 0.0032 según datos publicados en el sitio web "Bicycle Rolling Resistance" para los neumáticos montados. El C_{DA} se calculó utilizando el dispositivo Notio y el modelo matemático de Martin. Todos los datos de potencia y velocidad fueron revisados para detectar valores atípicos mediante el método del rango intercuartílico (IQR). Se realizó un análisis de potencia a priori para establecer el tamaño mínimo de la muestra utilizando el software G*Power versión 3.1.9.7 (Faul et al., 2007). El análisis mostró que un criterio de significación $\alpha = 0.05$, para alcanzar un 80 por ciento de potencia, requería un tamaño de $N = 12$.

Se verificó la normalidad a través la prueba de Shapiro-Wilk y gráficos Q-Q (cuantil-cuantil). Se realizó un ANOVA de medidas repetidas para analizar los efectos intra-sujeto para la interacción método-entorno, seguido de comparaciones post hoc ajustadas mediante el método de Holm, con el nivel de significación establecido en $\alpha = 0.05$. La magnitud de las diferencias se analizó utilizando la MD y las diferencias medias estandarizadas (d de Cohen, reportadas como tamaño del efecto [ES]).

El acuerdo entre entornos para cada método se determinó utilizando gráficos de Bland-Altman, con LoA presentados como sesgo $\pm 1.96 \times SD$. La fiabilidad absoluta se informó utilizando el SEM, calculado como $\sqrt{MSE}$ donde MSE es el término de error cuadrático medio del ANOVA de medidas repetidas. Se calculó el SEM95, que representa el intervalo de confianza del 95% para el error estándar de medición, utilizando $SEM \times 1.96$. Para la fiabilidad relativa, se utilizaron el CV%, el ICC y sus intervalos de confianza. Las estimaciones del ICC y sus IC95% se basaron en la puntuación media ($k = 4$), acuerdo absoluto y el modelo de efectos aleatorios de dos vías.

También se informó la desviación estándar intra-sujeto (s_w) para cada configuración como medida de repetibilidad (Bland & Altman, 1996). Todos los análisis estadísticos se realizaron utilizando el software de código abierto JASP (JASP Team, 2024).

Discusión

Esta tesis doctoral proporciona una evaluación sobre la validez, fiabilidad y aplicación práctica del dispositivo Notio para el cálculo del C_{DA} en ciclismo. Los resultados obtenidos a través de tres estudios complementarios permiten establecer conclusiones relevantes sobre su utilidad como

herramienta alternativa a los métodos tradicionales. El análisis de validez del C_{DA} calculado por Notio frente a los modelos matemáticos de VE y Martin demostró una alta correlación, con ICC superiores a 0.8, indicando un buen nivel de acuerdo entre métodos. A pesar de este acuerdo, ninguno de los tres métodos fue suficientemente sensible para detectar cambios de posición, probablemente porque los participantes, todos ciclistas profesionales, ya tenían una posición inicial optimizada. Este resultado coincide con los hallazgos de Valenzuela et al. (2020), quienes también reportaron una buena correlación entre Notio y otros métodos validados.

Sin embargo, nuestros datos revelaron un aspecto novedoso. Aunque los valores absolutos de C_{DA} son comparables, la dirección de los cambios detectados entre diferentes posiciones fue diferente entre Notio y los modelos matemáticos. Esta discrepancia podría conducir a diferentes recomendaciones sobre la posición ideal del ciclista. Estos resultados refuerzan la idea de que Notio tiene limitaciones para detectar cambios aerodinámicos pequeños.

En cuanto a los valores absolutos de C_{DA} , los calculados por Notio en nuestro estudio fueron ligeramente inferiores a los obtenidos mediante los modelos matemáticos, un 2% menos que VE y un 4% menos que Martin, lo que contrasta con los datos publicados por Valenzuela et al. (2020), donde los resultados de Notio fueron un 1.6% más altos que los del modelo de Martin. Esta diferencia podría deberse a varios factores, como la posible discrepancia entre las mediciones de los tubos de Pitot de diferentes unidades Notio, ya que la reproducibilidad entre dispositivos aún no ha sido evaluada. Otro factor podría ser que en Valenzuela et al. (2020), Notio y Martin utilizaron diferentes fuentes para incorporar los datos de temperatura, humedad y presión, mientras que, en nuestro estudio, ambos sistemas utilizaron la misma fuente para estos parámetros ambientales.

El resultado de C_{DA} más alto mostrado por el modelo de Martin puede explicarse por la variable que este modelo incorpora para considerar la dinámica del ciclismo en pista, que corrige a la baja la velocidad medida por el velocímetro en la rueda (Martin et al., 2006). Esto sugiere que tanto Notio como VE podrían proporcionar valores de C_{DA} más bajos que los reales en condiciones específicas de ciclismo en pista.

Las diferencias encontradas entre la posición basal y C2 en los tres sistemas fueron de 0.009 m², con el mayor cambio registrado de 0.011 m², medido por Notio, entre la posición basal y C1. Aunque no encontramos significación estadística entre cambios de posición, las mejoras en C_{DA} según nuestros cálculos podrían suponer un aumento de velocidad de 0.55 km/h, lo que se traduciría en una mejora de tiempo de aproximadamente 1

minuto en una contrarreloj de 40 km, o un ahorro de potencia de entre 10 y 11 vatios a una velocidad constante.

La validación de la velocidad del viento calculada por Notio bajo condiciones controladas de túnel de viento proporciona información fundamental sobre la precisión de esta variable clave en el cálculo del C_{DA} . Después de la calibración recomendada por el fabricante, las diferencias en comparación con el HWA se redujeron al 0.76%, demostrando que Notio puede medir la velocidad del viento con buena precisión en rangos de velocidad habituales en ciclismo (≈ 30 -50 km/h). Antes de la calibración, Notio medía velocidades un 6.44% más altas que el HWA, con una diferencia absoluta de 2.90 km/h, lo que confirma la necesidad del proceso de calibración para asegurar la validez de la medición.

Este resultado contrasta con el reportado por Van Erp et al. (2021), quienes encontraron problema de precisión en la velocidad del viento con diferentes ángulos de guiñada. Nuestros datos indican que Notio mantiene su precisión incluso con ángulos de hasta 20° , lo que es coherente con las características aerodinámicas de los tubos de Pitot de cabeza hemisférica descritas por Walchner (1939), quien reportó errores de solo un 1% en ángulos de hasta 15° y menos del 2% para 20° . Otros autores también han mostrado coeficientes de presión cercanos a 1 para ángulos de hasta 20° , respaldando nuestros hallazgos (Beck et al., 2010). Además, en competición debido a las altas velocidades, se estima que solo el 5% del viento podría superar los 20° de guiñada (Cooper, 2003), siendo menos crítica la precisión en ángulos de guiñada extremos.

La disminución de la precisión observada a velocidades más altas (≈ 60 km/h) representa una limitación significativa. Considerando que muchas pruebas profesionales de contrarreloj se desarrollan a velocidades que, sumadas al viento de frente, pueden superar esta velocidad, se debe tener precaución al interpretar resultados en estas condiciones. Este hallazgo sugiere la necesidad de calibrar el dispositivo a velocidades cercanas a las de la evaluación aerodinámica, un fenómeno también observado por Van Erp et al. (2021), quienes encontraron que el error aumentaba a velocidades inferiores o superiores a la velocidad de calibración. En su estudio, Notio mostró una mejor respuesta en este aspecto que Aeropod, otro modelo de aerosensor.

En cuanto al análisis de fiabilidad, Notio mostró buenos valores con un coeficiente de variación (CV%) de 1.02 y un error estándar de medición (SEM) de ± 0.455 km/h, aunque estos resultados fueron aproximadamente un 50% inferiores a los del HWA (CV% = 0.59, SEM de ± 0.261 km/h). En las evaluaciones aerodinámicas, la fiabilidad suele ser un factor preferible

incluso sobre la precisión absoluta, ya que el objetivo habitual es comparar configuraciones, y no tanto conocer el valor real y preciso del C_{DA} .

Respecto a la consistencia de las mediciones entre entornos interiores y exteriores, Notio presentó una ventaja sobre el modelo de Martin. Mientras que Martin mostró diferencias significativas (2.4% más alto en interior, $p < 0.001$), Notio mostró valores consistentes independientemente del entorno de prueba. Esta característica es particularmente valiosa considerando que, aunque las evaluaciones en velódromo ofrecen condiciones más controladas, no todos los ciclistas pueden tener acceso a instalaciones de pista cubierta, y la conducción en exterior es más representativa de la realidad para la mayoría de los eventos ciclistas. La capacidad de Notio para proporcionar mediciones comparables en ambos entornos facilita el uso de esta herramienta. Esta consistencia se debe posiblemente a la capacidad del tubo Pitot-estático para medir correctamente la presión dinámica experimentada por el ciclista, proporcionando datos más precisos sobre el viento real al que se enfrenta el ciclista.

Sin embargo, el hallazgo más relevante desde una perspectiva práctica está relacionado con la sensibilidad de los métodos evaluados. Ninguno de ellos, incluido Notio, demostró la capacidad de detectar de manera fiable pequeños cambios aerodinámicos, ya que el SEM95 superaba las diferencias observadas entre diferentes configuraciones de equipamiento. Esta incapacidad para identificar con precisión cambios de este tamaño limita su aplicación en el ciclismo de alto rendimiento donde incluso pequeñas mejoras pueden marcar la diferencia.

Poniendo esta magnitud en perspectiva, en una contrarreloj como la del Giro de Italia 2024 de 40.6 km, en la que Tadej Pogačar registró una velocidad de 47.1 km/h, según nuestros cálculos utilizando la fórmula de Martin, una mejora de 0.001 m^2 en el C_{DA} se traduciría en una ventaja de 11 segundos, lo que podría decidir el resultado de la clasificación general o la victoria de etapa.

Diversos factores contribuyen a esta limitación en términos de sensibilidad. Primero, las mediciones realizadas en un velódromo presentan limitaciones técnicas, como la necesidad de mantener una posición constante mientras se interactúa con la geometría variable de la pista. Fitzgerald et al. (2021) apuntan a que esto requiere ajustes constantes en inclinación, velocidad, cadencia y potencia, lo que podría comprometer la fiabilidad de las mediciones repetidas, enmascarando pequeñas mejoras aerodinámicas.

En entornos exteriores, incorporar con precisión el viento en la ecuación de cálculo del C_{DA} representa una dificultad adicional. Además, se añade el

desafío de reproducir de manera precisa la misma postura corporal entre intentos lo que genera una fuente de variabilidad. Incluso bajo circunstancias controladas de túnel de viento se ha podido comprobar, que mínimas modificaciones en la posición de la parte superior del cuerpo en particular en la altura de la cabeza y el ángulo del cuerpo pueden influir de manera considerable en el C_{DA} tal y como indican Crouch et al. (2021).

El error del potenciómetro es otro factor importante. Rielves et al. (2021) reportaron una fiabilidad absoluta de $\pm 6.4W$ para el mismo modelo utilizado en esta investigación, que según cálculos basados en la fórmula de Martin podría traducirse en una variabilidad de C_{DA} de aproximadamente $\pm 0.006 m^2$. Otros estudios sobre validación de potenciómetros utilizados en ciclismo reportan CV entre 0.4 y 3% (Bertucci et al., 2005; Maier et al., 2017; Pallarés y Lillo-Bevia, 2018), que pueden traducirse en variabilidades de potencia cercanas a la mencionada. Esta magnitud de error instrumental por sí sola, supera muchos de los cambios aerodinámicos que se pretenden detectar en un protocolo de evaluación aerodinámica.

Además, la densidad del aire es otro factor que influye en los cálculos del C_{DA} . En nuestras mediciones en exterior, observamos cambios en la densidad del aire a lo largo del protocolo con el mismo ciclista de hasta un 3%, principalmente debido a variaciones de temperatura. Underwood (2012) reportó una incertidumbre del 0.4% en el cálculo de la densidad del aire bajo condiciones específicas (20°C, 1000hPa), que según nuestros cálculos basados en la fórmula de Martin podría traducirse en un error aproximado de $0.001 m^2$ en el cálculo del C_{DA} .

Nuestros resultados pueden compararse con los de Kordi et al. (2021), quienes analizaron el rendimiento de Notio en un velódromo cubierto. Su rango de s_w ($0.001-0.003 m^2$) fue ligeramente inferior al observado en nuestro estudio ($0.002-0.005 m^2$). Esta diferencia podría atribuirse a su muestra de ciclistas de pista de élite, quienes supuestamente serían más consistentes en la replicación de posición.

Por otro lado, Valenzuela et al. (2020) reportaron un s_w de $0.015 m^2$, tres veces mayor que nuestro valor promedio más alto y cinco veces mayor que el valor máximo reportado por Kordi et al. (2021). Esta alta variabilidad muestra una limitación en la capacidad del sistema para detectar cambios reales de C_{DA} entre diferentes configuraciones. El hecho de utilizar en su estudio un potenciómetro CycleOps PP1 con un CV entre 1.6 y 3.7% según Pallarés & Lillo-Bevia (2018), podría haber contribuido a esta mayor variabilidad. Además, su muestra de ciclistas entrenados, pero no de élite probablemente dificultó la replicación de posiciones entre intentos, especialmente considerando que evaluaron tres configuraciones que incluían

una posición erguida, que permite una mayor movilidad articular en codos y cadera.

Más allá del tipo de posición adoptada, las condiciones en exterior suponen una dificultad añadida para garantizar la repetibilidad de las mediciones de C_{DA} . En este sentido, Merkes et al. (2019) observaron una alta variabilidad en las pruebas de campo realizadas en diferentes posiciones de sprint de ciclistas. Los autores reportaron CV altos para la misma posición, entre 9.1% y 16.0%. Incluso después de una semana de entrenamiento y una sesión de familiarización, comprobaron que obtener mediciones precisas de C_{DA} en posiciones de sprint seguía siendo difícil. Atribuyeron esta variabilidad a la incapacidad de los ciclistas para mantener una posición estable, así como a la variabilidad inherente de las condiciones en exterior.

El hecho de que diferentes estudios ofrezcan resultados contradictorios pone de manifiesto la importancia de tener en cuenta variables como el tipo de potenciómetro utilizado, la experiencia de los ciclistas y la metodología particular de evaluación aerodinámica al interpretar los datos de C_{DA} .

Conclusiones

Notio muestra una alta correlación con otros modelos matemáticos validados en el cálculo del C_{DA} absoluto. Sin embargo, la dirección de los cambios detectados entre diferentes posiciones difiere entre Notio y los modelos matemáticos, lo que podría traducirse en diferentes recomendaciones sobre la posición óptima en ciclistas de élite.

Respecto al cálculo de la velocidad del viento, el aerosensor Notio permite obtener registros precisos en un amplio rango de velocidades y ángulos de guiñada después de un proceso de calibración en un túnel de viento. Los datos muestran que Notio calibrado a una velocidad cercana a la de uso permite un cálculo fiable y preciso, aunque su fiabilidad fue menor que la de un HWA. Sin embargo, debido a la influencia de la velocidad del viento en la resistencia aerodinámica, pequeños errores en esta medición podrían traducirse en valores considerables de C_{DA} , lo que podría afectar significativamente a su utilidad práctica.

En la evaluación de la consistencia en el cálculo de C_{DA} entre entornos interiores y exteriores, Notio muestra resultados comparables, sin diferencias significativas entre ambos. En contraste, el método de Martin presenta valores de C_{DA} significativamente más altos en interiores. Sin embargo, ninguno de los dos métodos pudo detectar diferencias estadísticamente significativas entre las diferentes configuraciones de equipamiento probadas.

Para el uso correcto de aerosensores en ciclismo, se recomienda considerar que aunque Notio muestra alta correlación con modelos matemáticos validados en el cálculo del C_{DA} absoluto, la dirección de los cambios detectados entre diferentes posiciones puede diferir, lo que podría resultar en diferentes recomendaciones sobre la posición óptima; calibrar el dispositivo a velocidades similares a las de la prueba de evaluación prevista; evaluar la fiabilidad del potenciómetro utilizado antes de las pruebas, contextualizando en términos prácticos cómo este error impacta en la fiabilidad del cálculo del C_{DA} ; y realizar múltiples ensayos para cada configuración probada reportando valores promedio junto con SEM95 para una interpretación más precisa de los cambios aerodinámicos reales.

En conclusión, aunque Notio representa un avance significativo en términos de accesibilidad en las evaluaciones aerodinámicas en ciclismo, y proporciona mediciones válidas de C_{DA} , su sensibilidad, al igual que la de los modelos matemáticos evaluados, es insuficiente para detectar pequeños cambios aerodinámicos que podrían ser decisivos en competición.

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Validity of a novel device for indoor analysis of cyclists' drag area

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Abstract

Purpose: Cyclists need to measure aerodynamic resistance accurately and reliably, as well as economically. Devices such as Notio Aerostick, an equipment device that includes one pitot tube, have appeared for this purpose. The aim of this study is, therefore, to test the reliability and degree of agreement in the evaluation of the CdA (coefficient of aerodynamic drag), assessed by means of the Notio Aerostick compared to the Virtual Elevation (VE) and Martin mathematical models. **Method:** Seventeen professional cyclists rode in a 250-metre-long velodrome covered with a concrete surface with their own time trial bikes. Each cyclist completed three rides of 15 laps at constant speed for the evaluation of the CdA, each of them in a different position [Baseline (B), Change 1 (C1) and Change 2 (C2)]. **Results:** The differences in CdA between methods were found for Martin in comparison with VE in all positions ($p < .001$) and with Notio Aerostick in B and C2 ($p > .05$). About differences of CdA for each method, considering between position changes, the results were the same for VE and Martin, but different for Notio Aerostick. **Conclusions:** Findings suggest that, notwithstanding Notio Aerostick is valid if we compare CdA values with respect to VE, since the direction of their between-positions CdA changes differs, the results of their aerodynamic evaluation could lead us to recommend different final setups. We need studies that evaluate different units of the Notio Aerostick device as well as the reliability and precision of each sensor that includes Notio Aerostick.

Keywords

Coefficient of drag; cycling; mathematical models; testing; endurance; pitot-tube

Highlights

- The CdA calculated by the Notio Aerostick and VE, a mathematical model previously validated, can be interchangeable, however the final position recommended by each method may be different, since the changes in the following position are given by the changes of the CdA in the previous position.
- None of the three methods allowed elite cyclists to measure statistically significant differences between the proposed setups.
- Although the CdA differences between positions were not significant, they can be decisive in the final result of a time trial competition.

Introduction

In recent years, interest in the study of aerodynamics in cycling has been increasing (Malizia & Blocken, 2021). Composed of different categories of resistance such as form, frictional, induced and interference (Jobe, 1984), aerodynamic drag becomes a key factor, especially on flat stages and time trials where speeds of over 40 km/h can be achieved (Martin et al., 2006). At this speed, 96% of the total power required is used to overcome air resistance (Martin et al., 2006).

Knowing how, and at what magnitude, resistive aerodynamic forces are generated when moving forward,

enables us to take the necessary measures to optimise the aerodynamic component generated by the cyclists during pedalling (Jeukendrup & Martin, 2001), improving their performance. Among the techniques described for assessing this aerodynamic resistance in cycling, the wind tunnel is the gold standard; it is a reliable and reproducible method, although limited by accessibility and cost (Brownlie, 2019). Furthermore, the conditions simulated in a wind tunnel are not quite the same as those experienced by a cyclist in a velodrome or on the road (Malizia & Blocken, 2020).

A second approach is Computational Fluid Dynamics (CFD), which is very popular in research and other sports

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such as Formula 1, but this is equally difficult to access for most athletes; with a high cost when it comes to processing and interpreting data reliably (Malizia & Blocken, 2020). Alongside these is the so-called Ring of Fire, used to assess the punctual aerodynamic drag, although this is not very popular as it requires specific equipment that is not very accessible (Spoelstra et al., 2019). Finally, there are also field tests such as deceleration tests, constant speed tests and tests of section. All these use formulas that are solved according to the principle of energy conservation, using variables measured by different sensors that are adjusted with fixed values reported in the scientific literature (Malizia & Blocken, 2020).

In view of the aforementioned popularity of these sports, several methods have recently appeared with the aim to measure aerodynamic drag in a reliable and accurate, but also practical and affordable way. These include mathematical models, such as Virtual Elevation (VE) (Dyer & Disley, 2018) and the Martin's Model (Martin et al., 2006), but also aerosticks devices such as the Notio Aerostick (Argon 18; Montreal, Canada), AeroLab.tech (Strathcona Calgary, Canada), and Velocomp LLC (Stuart, Florida, EE.UU). The main feature of this devices is that it includes a pressure sensor capable of measuring wind speed, which together with other external sensors resolve an energy balance equation to obtain a composite value that includes the aerodynamic drag coefficient multiplied by the frontal area; that is, the so called coefficient of aerodynamic drag (C_dA) (Kordi et al., 2021; Valenzuela et al., 2020). In the case of aerostick Notio Aerostick, it uses its own equation that has not been published. With regard to the mathematical models VE & Martins, and their energy balance equations, further details can be consulted at references (Dyer & Disley, 2018; Martin et al., 2006) respectively.

To our knowledge, only two articles have been published to date that analyse the reliability and validity of the Notio Aerostick device (Kordi et al., 2021; Valenzuela et al., 2020). Neither of these analysed its sensitivity for detecting position changes when assessing C_dA in an aerodynamic assessment protocol, and in a real context with professional cyclists. The aim of this study is, therefore, to test the reliability and degree of agreement in the C_dA evaluation of the aerostick Notio Aerostick (Kordi et al., 2021; Valenzuela et al., 2020) compared to the VE (Dyer & Disley, 2018) and Martin (Martin et al., 2006) mathematical models, both previously validated with the gold standard wind tunnel method. Changes in positional adjustments are considered for further comparisons. As main hypothesis, the authors expected a high grade of agreement and notable associations

between the aerostick Notio Aerostick and the mathematical models.

Material and methods

Participants

Seventeen professional cyclists (63.5 ± 8.1 kg, height: 175 ± 9 cm) voluntarily participated in the study. The inclusion criteria were having extensive time trial cycling experience and being a professional cyclist. Before the participation, they were informed of the purpose and risks of the study and provided with a written informed consent form. None of the cyclists had any injuries or health problems. Written informed consent was obtained from each participant. The study was approved by the Ethics Committee of the University of Valencia (Valencia, Spain) and was conducted in accordance with the Declaration of Helsinki (2013) and the international research standards (Harriss, Macsween, & Atkinson, 2019).

Study procedure

The recording process was conducted in a 250 m-long concrete-surfaced indoor velodrome (Tafalla, Navarra, Spain), where the cyclists rode their own time trial bicycles. The participants were weighed together with their bikes and equipment at the start of the test. Each rider completed three rounds of 15 laps at a constant speed to assess the C_dA , each time in a different position; Baseline (B), Change 1 (C_1), and Change 2 (C_2).

In all cases the 15 test laps were preceded by 12 additional laps to calibrate the Notio Aerostick device, with the riders maintaining the same position and speed at which the test was performed, according to the manufacturer's instructions. In addition, 2 launched laps were included between the 12 calibration laps and the 15 test laps to reach the target speed and position. A slightly lower speed than competition speed – between 40 and 45 km / h – was chosen, in order to favour a stable position that would not be compromised by the intensity of the exercise. The rest time between tests was 10 minutes, which was used to make the appropriate changes to the position of the bike.

The speed of the bicycle was measured using a speedometer placed on the front wheel. Power was measured with a Power2max powermeter (Saxonar GmbH, Walhufen, Germany) installed on the cranks. The potentiometer was calibrated to zero before the measurement. Riders received speed feedback through a cycle computer Garmin 520 installed on their bike. At

the same time, we checked on the track that the lap times were as indicated.

The instructions given to the cyclist were that, in each position, they should not change gear; they should maintain a stable speed and position on the bike, and they should try to ride the entire test above the black line painted on the concrete that delimits the length of the velodrome. The position changes were achieved by modifying the height, reach and width of the handlebars and elbow-rests, as the commercial contracts for professional cyclists limited any possibility of changing the material. On the other hand, when testing sensibility, it may be a limitation of the study the need to make all the position changes within the UCI regulations. Each change was made taking into account the initial position of the cyclist, looking for the best possible improvement in each of them in terms of reducing the frontal area without compromising stability and comfort. We took into account the effect of changes in the CdA caused by three positional adjustments.

Finally, temperature, humidity, partial pressure, and atmospheric pressure were continuously recorded by the Notio Aerostick device. As a result, the average weather conditions were: $20^{\circ}\text{C} \pm 2.6$ temperature, $51.9 \pm 4\%$ humidity, and 1193 ± 11 kPA atmospheric pressure.

Aerodynamic drag coefficient assessment

As indicated above, three methods were used to analyse the changes in position, with the aim of studying the degree of agreement between them.

Notio Aerostick (Argon 18; Montreal, Canada) is an aerostick device that incorporates a differential pressure sensor, a barometric pressure sensor, an accelerometer and a gyroscope. The data provided by these sensors, together with external speed and power sensors, and an own energy conservation formula, allow the Notio Aerostick to estimate the CdA. The data recorded in the test must be transferred from the device to a computer for processing with a specific programme, based on the original software of Golden Cheetah.

The VE method (Chung, 2012) uses a mathematical model incorporated into the Golden Cheetah training analysis software through the "Aerolab" app. This method was originally intended to calculate the result of two unknown drag variables, the Coefficient of Rolling Resistance (Crr) and the CdA, by recording at different speeds. However, in this case, the Crr value was incorporated into the system as a known measure -see below-.

The third system is a mathematical model proposed by Martin, specifically for track cycling. The special feature of this formula is its inclusion of the variable height of the centre of mass, to account for the

centripetal force experienced by the cyclist in curves, which causes the speed of the bicycle to differ from the speed of the centre of mass (Martin et al., 2006).

Hence: Crr was set at 0.0025 for all three models in accordance with previous research involving concrete velodrome surfaces (Martin et al., 2006). We can find different Crr values in the literature, such as those of 0.003 reported by Grappe (Grappe et al., 1997) also for velodrome, although in this case, as the main objective of the study are to report changes in the CdA, it is not so important that the value are exact, as this is not modified throughout the trials.

Importantly, we ensured that temperature, speed, and weight, the three factors that can modify the Crr, were constant throughout the test. More specifically, the transmission system efficiency was set at 97.7%, in line with previous research on components of wear-free transmission and well-lubricated (Martin et al., 2006); the centre of mass height was considered as the distance between the top of the saddle and the ground (Martin et al., 2006). The wind speed for the VE and Martin mathematical models -as it was an indoor velodrome-, was considered zero, following the indications of other authors (Underwood & Jermy, 2010a, 2010b), while for the Notio Aerostick model it was calculated by the partial pressure sensor, according to the manufacturer's indications. When calculating the formula, the Notio Aerostick system includes acceleration; in the mathematical models of VE and Martin this acceleration was considered to be zero, since the instructions given to the cyclist were to maintain a stable speed at all times.

To conclude, the rider fatigue was not considered since the duration of the intervals at the target intensity is below the limit performance of our elite cyclists.

Statistical analysis

The statistical analysis was performed using a spreadsheet and SPSS software (SPSS 25.0, Inc., Chicago, IL). The alpha significance was set at 0.05. The measurements were expressed as 95% confidence intervals (CI). To ensure the normality of the sample, the Shapiro-Wilk normality test was performed. A repeated measures analysis of variance (ANOVA) was performed to determine whether there were significant differences in speed and power between the three positions. A second repeated measures ANOVA was performed to examine the CdA differences between the methods for each change of position, followed by intraclass correlation (ICC) analysis and the degree of agreement of the CdA values for the 15-lap stretches for all positions for the three methods, which were plotted on a Bland-

Altman graph using RStudio software (Version 1.4.1103). Additionally, the differences between the CdA results for each method between position changes were calculated, as were the Pearson correlation coefficients (r) of these CdA differences, and Typical Error of Measurement (TEM). Finally, a linear regression was run to determine the predictive ability of the different measurement systems with respect to one another.

The magnitude of the differences (effect size; ES) was analysed using partial eta squared (η^2). The ES values 0.01, 0.06, 0.14, were considered small, moderate and large respectively (Cohen, 2021). The ICC was interpreted according to the following thresholds: high, >0.90 ; moderate, 0.80 – 0.90 ; low, <0.80 (Koo & Li, 2016). Limits of agreement (LoA) were represented as bias $\pm 1.96 \times \text{SD}$. Pearson's r values of <0.1 , 0.1 – 0.39 , 0.4 – 0.69 , 0.7 – 0.89 , 0.9 and 1 were considered insignificant, weak, moderate, strong, and very strong, respectively (Schober, Boer, & Schwarte, 2018).

Results

The participants rode at an average speed of 43.58 ± 1.6 km / h and with an average power of 287 ± 40 W during the different tests. No significant differences were found between the mean power at the different positions ($F = 1.158$; $p = .314$, $\eta^2 = 0.067$; $P_{\text{baseline}} = 291.5 \pm 41.9$ W; $P_{C1} = 284.0 \pm 42.0$ W; $P_{C2} = 286.6 \pm 39.6$ W), neither in the average velocities ($F = 0.227$; $p = .798$, $\eta^2 = 0.014$; $V_{\text{baseline}} = 43.45 \pm 1.43$ km / h; $V_{C1} = 43.62 \pm 1.79$ km / h; $V_{C2} = 43.68 \pm 1.63$ km / h).

The calculation of the CdA showed significant differences depending on the evaluation method used ($F = 12.282$; $p = .003$, $\eta^2 = 0.434$). Considering all the rounds and without taking into account the changes in position, Notio Aerostick gave the lowest CdA value (0.238 ± 0.024 m²), and Martin the highest (0.248 ± 0.021 m²), with significant differences between them ($p = .002$). Between these two methods, VE (vs. 0.243 ± 0.020 m²) only differed significantly from Martin ($p < .001$). These differences were reduced to a trend when comparing between positions ($F = 2.951$ $p = .085$, $\eta^2 = 0.156$; $\text{CdA}_{\text{baseline}} = 0.249 \pm 0.007$ km / h; $\text{CdA}_{C1} = 0.239 \pm 0.003$ km / h; $\text{CdA}_{C2} = 0.240 \pm 0.004$ km / h), and disappeared when considering the interaction Method*Change of position ($F = 0.150$; $p = .738$, $\eta^2 = 0.009$). Despite this, and as shown in Figure 1, posterior Bonferroni adjustments showed that while no method detected these minimal position changes in the aerodynamics ($p > .05$), the differences between the methods were confirmed and were evident for Martin compared to VE for all the positions ($p < .001$), as well as to Notio Aerostick at $\text{CdA}_{\text{baseline}}$ and CdA_{C2} ($p > .05$), Figure 2.

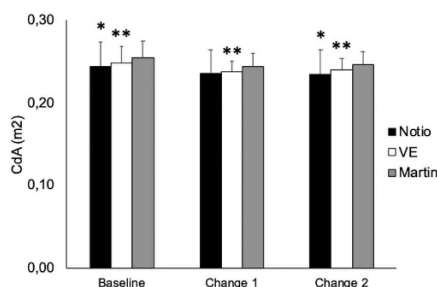


Figure 1. Changes in CdA considering three different positions for the aerostick Notio Aerostick vs. the Martin & Virtual Elevation mathematical models. * $p < .05$ vs. Martin for the same position. ** $p < .001$ vs. Martin for the same position

In terms of the agreement between the systems, Notio Aerostick presented a high ICC with VE but also a high TEM (ICC = 0.820 , 95% CI = 0.685 – 0.898 ; $p < .001$), similarly to the Martin model (ICC = 0.832 , 95% CI = 0.705 – 0.904 ; $p < .001$), although with a low bias ($\pm$ LoA) of -0.004 ± 0.017 m² and -0.009 ± 0.016 m², respectively (Figure 2). The two mathematical models, Martin and VE showed a very high ICC, (ICC = 0.999 , 95% CI = 0.998 – 0.999 ; $p < .001$), with a low bias ($\pm$ LoA) of -0.005 ± 0.001 m². When we observe the regression line calculated for the differences, in the Bland–Altman plot, between Notio Aerostick against VE and Martin, we find a proportional (non-constant) asystematic bias, with a positive trend in the differences as the magnitude of the measured variable increases. Meanwhile, when we analyse this between the two mathematical models, we can see that Martin vs. VE shows a proportional systematic bias (not constant), with a negative trend of the differences as the magnitude of the measured variable increases (Figure 3).

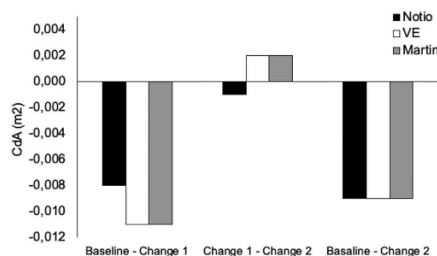


Figure 2. Differences between position changes for the aerostick Notio Aerostick vs. the Martin & Virtual Elevation mathematical models.

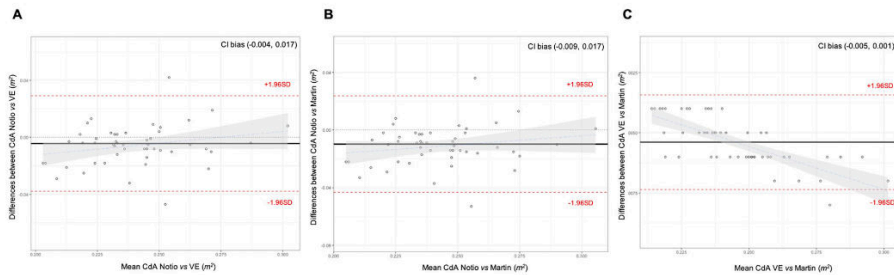


Figure 3. Agreement between the aerostick Notio Aerostick vs. the Martin & Virtual Elevation mathematical models. Subfigure A; comparison CdA Notio Aerostick vs. VE. Subfigure B; comparison CdA Notio Aerostick vs. Martin. Subfigure C; comparison CdA VE vs. Martin.

The analysis of Pearson's correlation for the data of CdA difference between position changes, between Notio Aerostick and the two mathematical models was significant and moderated; Notio Aerostick-VE: $r = 0.411$ $p = .003$; Notio Aerostick-Martin $r = 0.409$ $p = .003$, while between the mathematical models it was perfect: VE-Martin $r = 1$ $p < .01$. The results of the coefficient of determination (R^2) for this same data set are shown in Figure 4.

Discussion

The purpose of this study was to evaluate the validity and sensitivity to changes in cyclist position with respect to the measured CdA between the Notio Aerostick device (Kordi et al., 2021; Valenzuela et al., 2020) and two other mathematical models, VE (Dyer & Disley, 2018) and Martin (Martin et al., 2006). Our main finding is that, although the level of agreement of Notio Aerostick with both formulas is satisfactory ($ICC > 80\%$), with low and non-systematic error bias, and the differences in CdA are not significant in any of the positions, our results show that Notio Aerostick gives slightly lower values than those obtained by the

formulas. As expected, these confirm the differences and systematic bias, as a result of including the height of the centre of mass for indoor cycling, or not. On the other hand, none of the three systems (Notio Aerostick, VE, or Martin) was sufficiently sensitive to detect position changes, probably due to the already optimised initial position of the participants, as they were all professional cyclists. Again, Notio Aerostick exhibited a different behaviour, correlating moderately with VE and Martin, with respect to the changes in CdA measured between positions.

The CdA results calculated by Notio Aerostick were lower than those calculated by the mathematical models, 2% lower than VE and 4% lower than Martin. This contrasts with the data published by (Valenzuela et al., 2020), in which the CdA results calculated using the Notio Aerostick device were 1.6% higher than those calculated by the Martin model. The differences in these results could be explained by several factors. The first could be the possible variation between the pitot-tube registers of different Notio Aerostick devices, as the reproducibility between devices has not yet been analysed. The second reason is that, in the case of Valenzuela et al.

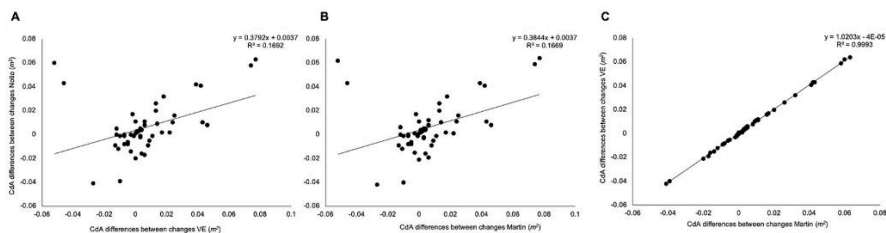


Figure 4. Direction of changes between the aerostick Notio Aerostick vs. the Martin & Virtual Elevation mathematical models. Subfigure A; differences between CdA Notio Aerostick vs. VE. Subfigure B; differences between CdA Notio Aerostick vs. Martin. Subfigure C; differences between CdA VE vs. Martin.

(2020), different temperature, humidity and pressure sources were used to compare the Notio Aerostick device with other measurement systems.

The fact that we obtained a higher CdA result with the Martin model can be explained by the variable that this model incorporates in an attempt to account for the specific physics of track cycling, correcting the speed measured by the speedometer downwards (Martin et al., 2006). This suggests that both Notio Aerostick and VE may actually give CdA lower values than the real ones in specific indoor cycling conditions.

The differences found between the baseline position and change 2 in all three systems were 0.009 m^2 , with the largest change recorded being 0.011 m^2 , as measured by Notio Aerostick, between the baseline position and change 1. Although we found no statistical significance between the position changes, the improvements in the CdA according to our calculations could mean a speed increase of 0.55 km/h , which would translate into a time improvement of around 1 minute over a 40 km time trial, or a power saving between 10 and 11 watts at constant speed. This shows that, even in the case of professional cyclists with extensive experience and an optimised baseline position, small positional adjustments could lead to significant performance improvements. The results are close to those measured by Valenzuela et al. (2020), although in that case they tested amateur cyclists and compared upright and aerodynamic positions. Our data offers a more realistic view of aerodynamic optimisation for professional cyclists, involving small adjustments from an already optimised position, in search of improved aerodynamics.

Using the same data sources for speed and power, as well as temperature, humidity, and barometric pressure for all three models, we were able to determine to what extent the differences in CdA are due to the particularities of each system. The differences between the results from the Notio Aerostick device and the two mathematical models can be explained by the data provided by the pitot-tube, the data processing, and the mathematical formula used by Notio Aerostick, which is neither published or reported by the manufacturer. The variation between the VE and Martin models can be explained by the centripetal force correction in the Martin model, observing that these measurement differences are systematically present in all the results.

On the other hand, although they shared the data sources mentioned above, and taking into account the fact that the wind conditions were the same in each measurement round, the differences between the CdA calculated by the Notio Aerostick device and the mathematical models were not systematic, a fact that we

attribute to the recording and processing of the data from the partial pressure sensor.

Regarding the data of change of CdA between positions, we found no significantly different values between the Notio Aerostick and VE, although we were able to see a certain degree of significance for the baseline position and change 2 recordings. On the other hand, we did find significant differences between the two mathematical models, VE and Martin. This contribution has a limited application in the field of aerodynamic assessment, as we assume that the CdA results from the different methods will not be interchangeable, since they include different sensors and variables in their calculations. However, it would be interesting to see if they respond in a similar way to the same changes of position, since the main objective of the exercise is to find the most aerodynamic configuration (Malizia & Blocken, 2020).

When we look at the CdA change data between the different positions, we can see that Notio Aerostick correlates moderately with the mathematical models. This allows us to state that, in an aerodynamic assessment protocol, the final position recommended, could be different depending on if we are using the Notio Aerostick device, or the mathematical models of VE and Martin. Our data contrasts with that obtained by other authors, (Kordi et al., 2021; Valenzuela et al., 2020) in which the Notio Aerostick recordings followed the direction of change measured in the wind tunnel in one case, and in the other, that of the mathematical models (Kordi et al., 2021; Valenzuela et al., 2020).

To sum up, the practical application of the new systems based on pitot-tube represents an important technical challenge that needs to be studied in depth to determine clearly the methodology of use, as well as its real applications and limitations.

Conclusion

The differences and the moderate correlation found between Notio Aerostick and the two mathematical models for the changes of CdA calculated between positions, suggests that these systems would not be interchangeable in the aerodynamic field-test evaluation in elite samples. Despite the absence of significant differences between the CdA assessment by the Notio Aerostick, and the validated mathematical-model Virtual Elevation, the differences in the direction of the CdA scores might lead to different setup recommendations, because changes in a following position are given by the improvement of the CdA in the previous one. These setup differences might become very relevant in an elite time trial competition, where minimum differences play a key role in the results.

Noteworthy, nor the Notio Aerostick, nor the mathematical models Virtual Elevation and Martin, had enough sensibility to reflect changes in the cycling position of our elite sample when the proposed changes are small (inside the rules). Future studies are required to compare measurements between different units of Notio Aerostick, as well as the reliability and precision of each of the sensors that make up this device.

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Manuscript 2

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Article

Validity and Reliability of Wind Speed Calculated by Notio in Comparison with a Hot-Wire Anemometer

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Abstract: Optimizing aerodynamic efficiency is crucial in competitive cycling, where aerodynamic resistance significantly limits performance. Devices like Notio have emerged to calculate the coefficient of drag area (C_{DA}) considering dynamic pressure data calculated by an integrated Pitot-static tube. This study aimed to evaluate the validity and reliability of Pitot-static tube calculations through wind speed (WS) data against a hot-wire anemometer (HWA). Sixty recordings were made, lasting 30 s each, in a closed-circuit wind tunnel at four different WS (≈ 30 to ≈ 60 km/h), and at five different yaw angles (0° to 20°). Initially, Notio showed WS 6.44% higher than HWA. The calibration process recommended by the Notio manufacturer reduced the differences to a non-significant 0.76%. Comparison of the WS of Notio calibrated and HWA only showed significant differences in the WS group of ≈ 60 km/h. There were no significant differences in the comparison of yaw angles groups. The reliability of Notio was worse than that of the HWA. In conclusion, Notio calibrated at a speed close to its use allows for reliable and accurate calculation of WS over a wide range of yaw angles under controlled wind tunnel conditions without the presence of a cyclist and bicycle. However, due to the influence of WS on aerodynamic drag, small errors in WS could translate into considerable values of C_{DA} for cycling performance.

Keywords: C_{DA} ; cycling; Pitot-static tube; reliability; validity; wind tunnel



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1. Introduction

In competitive cycling, aerodynamic resistance constitutes one of the primary factors limiting cyclists' performance, especially at high speeds. Approximately 90% of the total resistance encountered by a cyclist is aerodynamic in nature [1]. Therefore, optimizing the cyclist's position and equipment to reduce this resistance is crucial for enhancing performance and efficiency during competitions.

To assess and improve aerodynamic efficiency, the drag area (C_{DA}) is utilized, representing the combination of drag coefficient and the frontal area. Typically, in cycling, the calculation of C_{DA} in field tests has relied on mathematical models that, in many cases, either disregard wind speed (WS) or depend on data from nearby meteorological stations [2,3]. Alternatively, WS can be measured at a specific point along the route using anemometers, despite these methods often assuming a constant wind speed, which can introduce significant errors in C_{DA} calculations due to environmental fluctuations [4].

In this context, devices such as Notio (Argon 18; Montreal, Canada) have emerged as innovative tools designed to calculate $C_D A$ in field tests more accurately and efficiently. Notio integrates multiple sensors, including a Pitot-static tube, which allows for the measurement of dynamic pressure and, from these data, the calculation of the actual wind speed facing the cyclist. Utilizing a proprietary formula, Notio converts these measurements into $C_D A$ values, providing rapid and practical information that can be used by coaches, cyclists, and sports scientists to optimize the cyclist's position and equipment configuration [5,6].

The operational principle of Notio is based on measuring pressure differentials that, according to Bernoulli's equation, are related to wind speed. The primary advantage of Notio lies in its ability to provide real-time measurements in field conditions, facilitating informed decision-making to improve aerodynamic performance [7].

Despite its potential, the accuracy and reliability of Notio in measuring wind speed and, consequently, in calculating $C_D A$ have been subjects of debate in the scientific literature. To date, several studies have evaluated Notio's performance under field conditions with varied conclusions [2–5]. However, there is a notable lack of research that specifically examines the validity and reliability of Notio in controlled environments such as wind tunnels, where the device's capabilities can be assessed more precisely under different wind speed and yaw angle conditions.

The objective of this study is to evaluate the validity and reliability of wind speed measurements performed by Notio in comparison with a hot-wire anemometer (HWA) in a closed-circuit wind tunnel. To achieve this, tests were conducted under various wind speed and yaw angle conditions to determine Notio's accuracy in measuring airflow under controlled settings. This study focuses on evaluating Notio by comparing it to a HWA under controlled wind tunnel conditions, without the presence of a cyclist, to establish a solid foundation before proceeding to more complex field validations.

2. Materials and Methods

2.1. Experimental Procedure

The experiment was conducted in a closed-circuit wind tunnel located at the European University of Madrid, Spain (Figure 1). The wind tunnel comprises two distinct test sections: a high-speed test section with dimensions of 0.9 m in width, 0.9 m in height, and 3 m in length, capable of generating airflow velocities up to 150 km/h; and a low-speed test section measuring 1.8 m in width, 1.8 m in height, and 3.8 m in length, capable of producing airflow velocities up to 50 km/h. The wind tunnel is equipped with a 400-volt fan system controlled by specialized software (Oritia & Boreas, Granada, Spain), ensuring precise airflow generation. Previous experiments reported a turbulence intensity of 0.3% in the high-speed test section, indicating a stable and controlled airflow environment.

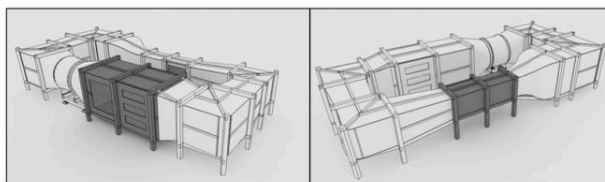


Figure 1. Three-dimensional representation of the wind tunnel, with the two test sections shaded, the low-speed test section on the left and the high-speed test section on the right. Original image of the wind tunnel manual with permission (Oritia & Boreas).

Two devices were used to measure wind speed within the high-speed test section: a hot-wire anemometer (HWA) and the Notio device (Figure 2). The HWA utilized in this experiment was a Kanomax Anemomaster™ 6036-CE model (Andover, MA, USA), which had undergone annual calibration with an accuracy of $\pm 1\%$ for the specific unit used.

It recorded wind speed (WS) using a telescopic one-dimensional probe inserted into the high-speed test section through a designated access port. Notio was securely attached to a metal support located at the base of the high-speed test section, ensuring stability and consistent positioning throughout the experiment. Both devices were centrally positioned relative to the side walls. The HWA and Notio were placed in the test section, with both devices positioned centered at Z-axis 150 cm from the beginning, centered at the Y-axis 45 cm above the floor, and at the X-axis 30 cm from the wall with 30 cm separation between devices (Figure 3). The blockage ratio of both devices was below 0.2%. The experimental arrangement was designed to mitigate wall effect and interference between devices to ensure measurement integrity [8,9].



Figure 2. Notio on the left and hot-wire anemometer Kanomax Anemomaster 6036-CE on the right. Original images from the manufacturer manuals with permission.

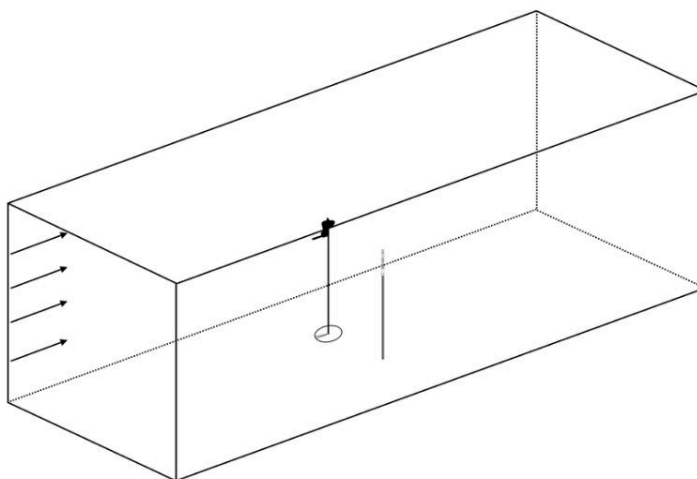


Figure 3. Scaled graphical representation of the arrangement of Notio and hot-wire anemometer in the high-speed test section of the wind tunnel.

A total of 60 recordings were made in the high-speed test section, each lasting 30 s. These recordings were divided into three equal blocks of 20 recordings each, covering four

different fan power settings corresponding to average wind speeds (WSs) as measured by the HWA: 21% fan power resulting in 29.52 ± 0.29 km/h, 28% fan power resulting in 39.59 ± 0.25 km/h, 37% fan power resulting in 50.42 ± 0.23 km/h, and 44% fan power resulting in 60.45 ± 0.29 km/h. Each wind speed setting was further tested at five different yaw angles (0° , 5° , 10° , 15° , and 20°) using a 360-degree protractor to precisely adjust the orientation of Notio relative to the airflow. Each recording commenced once the airflow achieved a stable velocity and continued for a duration of 30 s.

2.2. WS Calculation by Notio

Notio calculates wind speed using an integrated Pitot-static tube. Airflow enters through the front hole of the Pitot-static tube until stagnation occurs, and the total pressure is recorded. Through the side holes, which are not aligned with the direction of the wind, the static pressure is recorded. A pressure transducer is responsible for converting mechanical signals into electrical signals to be processed by the device. The dynamic pressure is calculated as follows:

$$q = P_0 - P_s \quad (1)$$

where q is dynamic pressure, P_0 is total pressure, and P_s is static pressure. A specific version of the Golden Cheetah software (v3.5/1.16.1), developed by Notio Technologies Inc., processes the dynamic pressure, temperature, humidity, and atmospheric pressure data recorded from Notio to calculate the WS shown in the summary of each record reported by the software, based on the Bernoulli principle defined as follows:

$$q = \frac{1}{2} \rho U_\infty^2 \quad (2)$$

and resolve it as follows:

$$U_\infty = \sqrt{\frac{2q}{\rho}} \quad (3)$$

where ρ is air density, and U_∞ is free stream velocity [10].

2.3. WS Calculation by HWA

An HWA calculates the WS indirectly based on the principle of convection cooling. It works by heating a thin wire to a constant temperature and then measuring the amount of electrical current needed to keep it at that temperature while the wind cools it. When the wind passes over the hot wire, it carries away the heat and requires more energy to keep it at the same temperature. By measuring the amount of energy necessary to maintain the constant temperature of the wire, the WS can be determined due to the correlation established between the electrical current supplied and the WS based on the empirical relationship developed through the calibration of the anemometer using air flows of known velocities [11].

2.4. Notio Calibration Process

Notio requires calibration before each use for correct operation, a process also common in Pitot-static tube systems installed on aircraft. This process corrects for possible pressure measurement errors due to local flow disturbances [12]. This is a one-point calibration process, in which Notio takes a reference value, from which it compares its initial reading and adjusts its calculation for subsequent measurements. Notio is a device designed for use in the field; so, in this case, the calibration process, although based on the same principle of the reference value as an adjustment point for subsequent measurements, differs from the usual calibration process.

To calibrate Notio in a field test with the bicycle, a ride of between 1600 and 3000 m must be completed in the case of performing the test on an indoor track, or two rides of the same distance mentioned, one going and one returning along the same route and consecutively, in the case of performing the procedure outdoors. The reference value in

the case of the indoor procedure comes from the speed sensor installed on the bicycle since, in this case, it assumes that there is no wind in the indoor track, and therefore the wind recorded by Notio will correspond exactly with the speed of the ride. For outdoor calibration, the reference value is based on the assumption that the wind experienced on the going route is equal in magnitude but opposite in direction to that on the return route, resulting in the wind speed considered by Notio being on average zero. The manufacturer recommends repeating this calibration process whenever there is a change in the cyclist's position with respect to Notio since the particular shape of the cyclist in each position will produce specific flow disturbances.

The Notio calibration process in this experiment was based on the reference value given by the HWA. A first recording was carried out simultaneously with the Notio and the HWA in the high-speed test section, as described in the experimental procedure, with a fan power of 21% (≈ 30 km/h) and a 0° yaw angle. The WS value recorded by the HWA was set up with the Golden Cheetah software responsible for interpreting the data recorded by Notio. With this reference value, the software compares the first record and calculates the calibration factor to correct this first record and the following ones and obtain the calibrated Notio (Notio_C) WS data.

By utilizing the HWA as a precise reference instrument under controlled, clean-air conditions, the calibration process established a reliable baseline for Notio_C. This calibration is based on the same underlying assumption as the manufacturer-recommended process, where both methods require a reference wind speed. However, in this experiment, the reference was directly obtained from the HWA measurements in a controlled environment, whereas in field calibrations, it is derived from the assumption of zero average wind speed over two consecutive sections. Extending this calibration to include cyclist-induced flow disturbances is crucial for validating Notio's performance in dynamic and variable field environments.

2.5. Statistical Analysis

Data are presented as Mean $\pm$ SD. The normality and variance of each variable were checked in each of the tests that required it. A repeated-measures ANOVA test was performed to study the validity WS of Notio and Notio_C against HWA. Post hoc mean comparisons were analyzed to find differences between WS of Notio_C and HWA for each group of different yaw angles and WS. The mean difference (MD) and its 95% confidence intervals (CI95), and the significance value (p), as well as Cohen's d as a measure of the effect size (ES) and its CI95, were reported. Agreement WS for Notio_C with HWA was determined using a Bland–Altman plot with limits of agreement (LoA) presented as a bias of $\pm 1.96 \times \text{SD}$ [13]. The proportional bias line was drawn using a linear regression of the differences between the methods in the average of the measurements, as well as their confidence interval [14]. Absolute reliability for Notio_C and HWA was reported using the standard error of measurement (SEM) and its CI95 (SEM95). To measure relative reliability, the coefficient of variation expressed as a percentage of SEM (CV%), the intraclass correlation index (ICC), and its CI95 were used. ICC and its CI95 were calculated based on the mean score ($k = 3$), absolute agreement, and the two-way random effects model [15]. Statistical analyses were performed with specific statistical software [16], setting the alpha of significance at 0.05 with Bonferroni correction.

3. Results

Repeated-measures ANOVA confirmed significant differences between the WS for Notio and HWA with a MD = 2.89, CI95: [2.47, 3.32], $p < 0.001$, ES = 5.36, CI95: [0.21, 10.51]. No significant differences were found between Notio_C and HWA with a MD = -0.34 , CI95: [-0.76 , 0.08], $p = 0.117$, ES = -0.63 , CI95: [-1.62 , 0.36] (Figure 4, Table 1).

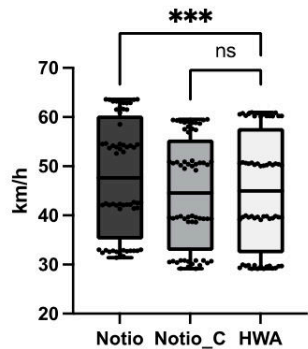


Figure 4. Comparative boxplot between Notio, Notio_C, and HWA wind speed (WS), including medians, interquartile ranges, and outliers, with statistical significance analysis: ns, non-significant; *** $p < 0.001$. Created with GraphPad Prism 10.

Table 1. Analysis of the mean wind speed registered by HWA, Notio and Notio_C.

		HWA (Km/h)		Notio (Km/h)		Notio_C (Km/h)	
		Mean $\pm$ SD	Mean $\pm$ SD	<i>p</i> -Value	ES	Mean $\pm$ SD	<i>p</i> -Value
Fan Power (%)	21%	29.52 $\pm$ 0.29	32.57 $\pm$ 0.47	<0.001 ***	5.65	30.28 $\pm$ 0.59	0.101
	28%	39.59 $\pm$ 0.25	42.11 $\pm$ 0.42	<0.001 ***	4.68	39.34 $\pm$ 0.40	1.000
	37%	50.42 $\pm$ 0.23	54.23 $\pm$ 1.31	<0.001 ***	7.06	50.44 $\pm$ 0.54	1.000
	44%	60.45 $\pm$ 0.29	62.65 $\pm$ 0.90	<0.001 ***	4.06	58.55 $\pm$ 0.85	<0.001 ***
Yaw Angle (°)	0°	44.94 $\pm$ 12.09	47.68 $\pm$ 11.88	<0.001 ***	5.06	44.37 $\pm$ 11.38	1.000
	5°	45.20 $\pm$ 12.22	47.78 $\pm$ 11.67	<0.001 ***	4.77	44.66 $\pm$ 10.90	1.000
	10°	44.94 $\pm$ 12.06	48.69 $\pm$ 12.41	<0.001 ***	6.94	45.19 $\pm$ 11.37	1.000
	15°	44.95 $\pm$ 12.08	48.03 $\pm$ 12.08	<0.001 ***	5.70	44.87 $\pm$ 11.30	1.000
	20°	44.95 $\pm$ 12.09	47.28 $\pm$ 11.94	<0.001 ***	4.33	44.18 $\pm$ 11.20	0.825

Abbreviations: SD, standard deviation; ES: effect size. Significant differences compared to HWA: *** $p < 0.001$.

The post hoc analysis between Notio_C and HWA for each yaw angle group did not show significant differences in any group, which supports the hypothesis that the yaw angle does not affect the WS calculation in Notio. On the other hand, a post hoc analysis between Notio_C and HWA between the different groups of WS revealed significant differences for the group with the highest WS (≈ 60 km/h) with a MD = -1.90 , CI95: $[-2.72, -1.07]$, $p < 0.001$, ES = -3.52 , CI: $[-7.77, 0.73]$.

The Bland–Altman plot for the degree of agreement between WS of Notio_C and HWA revealed a low bias of -0.342 , with a standard deviation of 1.20 . LoA $[-2.687, 2.003]$ shows that most individual differences are within this range, suggesting acceptable agreement between measurements. Regarding the proportional bias line, a non-constant systematic bias is observed, with a negative trend in the differences as the magnitude of the measured variable increases. This suggests that the discrepancies between measurements tend to widen as the WS increases. These results point out an acceptable agreement between measurements, despite it being important to consider the presence of systematic biases that could be relevant in certain contexts (Figure 5).

Finally, the analysis of the reliability of Notio_C and the HWA reflects low variability in both cases, although the results indicate better results for the HWA. The relative reliability for Notio_C shows CV% = 1.02 , ICC = 0.998 , and CI95: $[0.996, 0.999]$, and the HWA shows CV% = 0.59 , ICC = 1 , and CI95: $[0.999, 1.000]$. Regarding absolute reliability, Notio_C outcomes were SEM = ± 0.455 km/h and SEM95 = ± 0.891 km/h, whilst the HWA shows SEM = ± 0.261 km/h and SEM95 = ± 0.511 km/h.

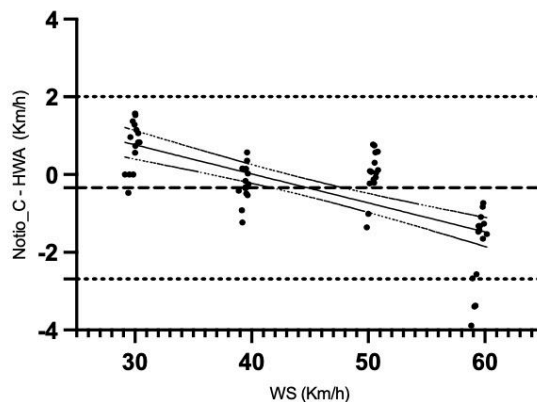


Figure 5. Agreement between Notio_C and HWA wind speed (WS) Bland–Altman plot. Created with GraphPad Prism 10.

4. Discussion

To our knowledge, this is the first study to analyze the validity and reliability of the WS calculated by Notio compared to an HWA in a wide range of WS and yaw angles. As the main finding, we observed significant differences in the WS between Notio and HWA, with the WS calculated by Notio being 6.44% higher than that calculated by HWA. Conversely, there were no significant differences between the WS of Notio_C and HWA in which case a difference of 0.76% is observed, in this case, the WS of Notio being lower than that of the HWA. In absolute terms, the WS of the Notio was higher than that of the HWA by 2.90 km/h. Carrying out the calibration process reduced the differences, in this case, with the values with Notio being 0.34 km/h lower than those with the HWA. The differences ranged between 0.12 and 8.17 km/h before calibration, and 1.57 and −3.88 km/h after, indicating that Notio, after the calibration process, may underestimate or overestimate the WS but with smaller differences, confirming the need to carry out the calibration process previously recommended by the manufacturer to guarantee the validity of the measurement.

As regards speed, Notio showed a similar error range with the HWA in the ≈ 30 , ≈ 40 , and ≈ 50 km/h groups, which was 2.04, 1.8, and 2.14 km/h, respectively, but greater in the ≈ 60 km/h group, with an error of 4.61 km/h. Although the methodology used was different and the validation device the authors used and its specifications are not mentioned, we find it interesting to mention the study by Van Erp et al. [16]. Our results contrast with theirs, which show that the differences between the WS calculated by Notio and the reference device were not influenced by speed. However, they follow a very similar dynamic to those also reported in this study, using a device also based on a Pitot-static tube called Aeropod™ (Aurora, CO, USA), in which they observed that the error increased at speeds lower or higher than the calibration speed. In this sense, our data suggest that calibrating at a WS of ≈ 30 km/h will not allow us to accurately calculate the WS at ≈ 60 km/h; therefore, the calibration process should be carried out at speeds close to those of the aerodynamic evaluation.

It should be noted, as already mentioned, that the calibration process in this wind tunnel experiment is specific and differs from that recommended in the C_{DA} evaluation with a bicycle in the field, although it is based on the same principle. Since the reference value of the Notio calibration process in this experiment was the exact WS recording of the HWA, this process could be more accurate than that performed during a field test, since the assumptions that there is no wind in an indoor track and the average wind for the go–return outdoor calibration ride is zero may not be met.

About the yaw angle, our results are also contradictory with what was found by Van Erp et al. [17]. In their study, Notio could not accurately calculate the WS at four different yaw angles from 5 to 20°. However, we did not find significant differences between the WS calculated by Notio and that calculated by the HWA for each yaw angle group from 0 to 20°. Several studies have analyzed the behavior of the Pitot tube in crosswind conditions. For example, Walchner [18] reported results for a Pitot tube with a hemispherical head design, in the same Notio shape, that at yaw angles up to 15°, only an error of 1% was measured, and there was one of less than 2% for 20°. Other authors also showed pressure coefficients close to 1 at yaw angles up to 20°, supporting this finding [19].

Concerning what has been mentioned, improving the aerodynamic position is especially relevant for events in which we compete alone, such as time trials. Due to the aerodynamic drag dependence of the WS, the aerodynamic evaluation must be performed under specific speed conditions. The mean speed of the winner of 55 time trials in 2023 in the men's professional cycling category was greater than 50 km/h, and in seven of them, it was greater than 55 km/h (ProCyclingStats, 2023). In addition to this average riding speed, the headwind that the cyclist may encounter must be added. In this context, the probability of reaching a yaw angle greater than 20° at a speed of 48 km/h is only 5% [20]. Therefore, our data support that Notio would be valid for an aerodynamic assessment in specific speed situations in which it will be difficult to find yaw angles beyond 20°.

Regarding the reliability analysis, the one in which records was compared under the same conditions; Notio showed a good value with a CV% of 1.02 and an SEM of ± 0.455 km/h, although it was almost 50% worse than that shown by the HWA (CV% = 0.59, SEM of ± 0.261 km/h). Reliability in an aerodynamic evaluation process is usually a preferable factor even over precision since the usual objective is to compare positions and materials to choose the most aerodynamic one, and not so much to know the real and precise value of the C_{DA} .

This research is not without limitations. It should be noted that this study is based on the validation of WS with Notio in a wind tunnel with a homogeneous flow, which has a limited practical application since the stability of the flow, especially in outdoor conditions, can be affected by factors such as wind gusts, turbulence generated by natural and artificial obstacles, atmospheric variations inherent to climate and topography, and the complex particularity of the atmospheric boundary layer. Moreover, during the entire experiment in the controlled environment of the wind tunnel, temperature, humidity, and atmospheric pressure—three variables measured by the sensors integrated into Notio and necessary for calculating wind speed—remained practically constant, with only minor variations. While this allowed us to minimize sources of variability, it may be considered a limitation that the device was not evaluated over a broader range of atmospheric conditions.

These variables directly affect air density and, consequently, the calculation of wind speed using Bernoulli's equation, which could influence the reliability and accuracy of the results in real-world settings [21]. For example, it is known that air density decreases with high temperature and increases with elevated atmospheric pressure, while humidity, although to a lesser extent, introduces additional variations that alter aerodynamic flow behavior [22]. This indicates that additional testing in an outdoor environment is essential to fully understand the response of the Notio Pitot-static tube to the dynamic conditions it will face in practical use.

On the other hand, although this study is based on the analysis of WS calculated by Notio, and we assume that the Pitot-static tube data must be of key importance, we do not know the C_{DA} calculation formula and, therefore, we cannot ensure the percentage of the error that a specific error in the precision and reliability of the Pitot-static tube will represent in the C_{DA} calculation. Furthermore, because energy dissipation occurs at a speed proportional to the square of the fluid speed, small error values could condition its practical application. Along these lines, it should be noted that to calculate the C_{DA} , Notio requires other internal and external sensors; so, errors in these sensors will also condition the results in the C_{DA} calculation.

To further illustrate the implications of wind speed accuracy on $C_D A$ estimation, consider a theoretical scenario based on Martin's widely recognized mathematical model [1]. For a 68 kg cyclist riding at 45.5 km/h and generating 417 W of power, a mere 1 km/h of error in wind speed would result in an error of approximately 0.010 m² in $C_D A$. In a 40 km individual time trial, this discrepancy in $C_D A$ could translate into a time difference of approximately 40 s. Such a margin is critical in competitive cycling, where victories are often decided by a few seconds.

Moreover, the calibration conducted in this study does not account for pressure disturbances introduced by a cyclist and bicycle, as the calibration was performed without these elements present. In real-world applications, the presence of a cyclist affects airflow around the device, creating an overpressure zone that can influence wind speed measurements. Consequently, Notio_C derived from this calibration may not fully represent performance under typical field conditions where a cyclist is present.

5. Conclusions

According to the results, Notio can accurately calculate wind speed in a wide range of yaw angles after a calibration process under controlled conditions without the presence of a cyclist on the bicycle, but there are certain limitations. The data obtained indicate the need to calibrate at speeds close to those of the aerodynamic evaluation to obtain precise data. Notio's reliability was good, but it was worse than that of the hot-wire anemometer.

In conclusion, Notio calibrates at a speed close to that used, and incorporates a precise and reliable wind speed value in its $C_D A$ calculation formula. However, small errors can impact in the practical field of aerodynamic evaluation. Furthermore, the absence of information on the $C_D A$ calculation formula, as well as the possible influence of errors in other internal and external sensors necessary for its calculation, leave a margin of uncertainty regarding the percentage of error that this could represent in the determination of aerodynamic resistance. Therefore, further research is required to fully understand the capabilities and limitations of Notio in aerodynamic evaluation in cycling.

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Manuscript 3

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The influence of the environment on the calculation of drag area in cycling: Contrasting results between indoor and outdoor field tests

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Abstract

This study analyzes two methods of calculating drag area (C_{DA}) in cycling, Notio and Martin, in indoor and outdoor environments, to determine if C_{DA} is consistent regardless of the testing environment. In addition, we assess the practical utility of both methods in both environments for selecting the most aerodynamic equipment. Twelve trained cyclists rode on an indoor cycling track and an outdoor road with four different settings combining different equipment. Each cyclist performed 4 attempts with each setting, completing a total of 32 segments of 1500 m, 16 segments in each environment. We calculated C_{DA} using both Notio and Martin methods. We then evaluated the repeatability and reliability of each method in both environments. C_{DA} comparison revealed significant differences between indoor and outdoor environments for Martin ($MD = 0.006 \text{ m}^2$; $SD = 0.009$; $p < 0.001$), but not for Notio ($MD = 0.001 \text{ m}^2$; $SD = 0.005$; $p = 0.569$), with indoor C_{DA} being consistently higher. Standard error of measurement (SEM) was similar across environments: Notio ($\pm 0.004 \text{ m}^2$ indoor; $\pm 0.003 \text{ m}^2$ outdoor), and Martin ($\pm 0.005 \text{ m}^2$ indoor; $\pm 0.006 \text{ m}^2$ outdoor). Notably, the 95% confidence interval of the SEM (SEM95), exceeded the C_{DA} changes observed in all settings relative to the baseline, for both methods and in both environments. Although Notio, unlike Martin, calculates C_{DA} consistently regardless environment, neither method demonstrated sufficient sensitivity to detect changes in C_{DA} in either environment, limiting their practical utility for selecting the most aerodynamic equipment.

Keywords

Aerodynamic resistance, Notio and Martin methods, pedal powermeter, time trial bike, velodrome

Introduction

One of the most popular methods to calculate drag area (C_{DA}) in cycling is a field test based on an energy conservation formula that considers different variables such as speed and power recorded by the cyclist with the bike on a specific route.¹ The test's popularity stems from its accessibility, cost-effectiveness, and speed compared to alternatives like wind tunnel or computational fluid dynamics (CFD).² It reproduces real-world wind flow conditions and enables assessment of cyclist comfort and biomechanics, crucial aspects for optimal performance.^{3,4} Aerodynamic field tests have been reported as a reliable and valid method for calculate C_{DA} , compared to the wind tunnel, considered the gold standard method.^{1,5,6}

Aerodynamic field tests can be conducted indoors or outdoors. Indoor evaluations potentially offer greater accuracy due to the assumed absence of wind.⁷ Outdoor tests present the challenge of incorporating real wind values into the

C_{DA} calculation equation due the presence and variable nature of wind.⁸ In outdoor evaluations, wind can be handled by recording it at a point along the route,⁹ estimating it using nearby weather stations,¹⁰ or omitting it, assuming equal wind intensity on outbound and return legs, a commonly used by commercial applications for

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field $C_D A$ calculations, such as Aerotune (Aerotune GmbH, Germany).

Recently, devices like Notio (Notio Technologies, Montréal, Canada) have emerged to enhance field test assessments, incorporating a Pitot-static tube to measure actual wind experienced by the cyclist. Several studies have evaluated Notio's performance with varied conclusions.^{10–14}

Although both Notio and Martin methods have been previously validated, to our knowledge, no study has directly analyzed the consistency of their results between indoor and outdoor environments. Given that outdoor testing is more accessible for most cyclists, the objectives of this study were to evaluate the consistency of $C_D A$ values across indoor and outdoor environments and to assess the practical usefulness of both methods in these different environments, when aiming to select the most aerodynamic equipment.

Methods

Participants

Twelve trained cyclists, 10 males and 2 females (age: 30 ± 7 years; weight: 71.5 ± 7.3 kg; height: 179.4 ± 5.3 cm) volunteered for the study. Inclusion criteria required previous experience in time trial bike competitions and velodrome riding. We informed participants of the purpose and risks involved and obtained their written informed consent. The University of Valencia's research ethics committee approved the study (REG-2024383, 05/05/2022).

Experimental protocol

We tested four different settings. The first was the baseline (time trial bike, road helmet, two-piece kit, 50 mm wheels). The other 3 varied the equipment item indicated by its name: Wheels (rear disc, front 88 mm), helmet (time trial helmet) and skinsuit (skinsuit). Testing was conducted indoors and outdoors on separate days. In each setting and environment, cyclists performed four 1500 m trials with approximately 5 min of recovery between trials. Each cyclist completed a total of sixteen 1500 m segments in each environment.

Cyclists subjectively determined their target speed, maintaining a high effort without compromising position. Although the target intensity was subjective, all cyclists were familiar and report their critical power. Post hoc analysis showed that the average power output during the trials was around 80% of their critical power, ensuring a consistent and sustainable effort across participants. The gear ratio chosen for the first test remained consistent for all subsequent tests, both indoors and outdoors. We weighed cyclists with each setting, including the bike and all equipment. Additionally, for indoor test, the center-of-mass height

was measured and standardized across all cyclists. The center-of-mass height was defined as the distance between the top of the saddle and the ground. This measurement is essential because, when cycling through a turn, the rider's center of mass travels a shorter path than the wheels due to the lean angle, resulting in a reduced speed. These assumptions provide a realistic approximation for the average data, despite not offering accurate results at any specific point.⁵

Bikes were equipped with a calibrated pedal powermeter (Assioma Duo, Favero Electronics, Italy) which has been validated in previous studies,^{15,16} and a Sigma 20502 magnetic speedometer (Sigma Sport, Germany) connected to the Notio device. We used a portable weather station (Weathermeter, Weatherflow, USA) to measure temperature, atmospheric pressure, humidity, wind speed, and direction. We set the transmission efficiency at 97.7% based on previous studies,⁵ and chose a C_{rr} (Coefficient of rolling resistance) value of 0.0032 according to data published for the mounted tires on the "Bicycle Rolling Resistance" website (<https://www.bicyclerollingresistance.com>). We inflated tires to 100 PSI for all tests.

Following the manufacturer's instructions, we performed an initial 3000 m calibration segment for Notio prior to each testing session. In the outdoor environment, this calibration consisted of 1500 m out and 1500 m back.

Indoor test

We conducted the indoor test in a 250 m official covered velodrome with a concrete track (Luis Puig, Valencia, Spain). The average meteorological conditions were $22.2 \pm 0.3^\circ\text{C}$ temperature, $56.5 \pm 4\%$ humidity, 1023.9 ± 6.9 mbar atmospheric pressure and 1.201 ± 0.007 kg/m³. We placed the weather station next to the start line, 2 meters from the outside of the track. Each 1500 m test consisted of 6 laps riding on the black line. Cyclists began pedalling for two laps before the test to gradually reach the target speed and position.

Outdoor test

We conducted the outdoor test on a straight, flat, asphalt road (coordinates 38.939191 and -0.480781). The average meteorological conditions were $22.9 \pm 5.0^\circ\text{C}$ temperature, $35.8 \pm 15.4\%$ humidity, 1023.5 ± 5.4 mbar atmospheric pressure, 1.199 ± 0.022 kg/m³ and each 1500 m test consisted of a 750 m out-segment followed by a 750 m back-segment on the same road in opposite directions. Cyclists began pedalling before reaching the starting line, marked with a white line on the road, allowing them to comfortably reach the target speed and position. After completing the first 750 m out-segment, cyclists decelerated to turn back and then accelerated again to complete the 750 m back-segment. We placed the weather station in

the middle of the 750 m segment, 2 meters to the right side of the road.

C_DA calculation

Using a smartphone, data was transferred to Notio cloud, to be subsequently downloaded to the Golden Cheetah sports training analysis software (version 3.5/1.16.1), which allowed the calculation of the calibration factor that would be used to subsequently calculate the C_DA values. For Martin's model, we used an adaptation of the Excel data analysis software template published by the authors in its two variants, indoor and outdoor.⁹ All power and speed data were reviewed for outliers using the interquartile range (IQR) method, defining outliers as those above the third quartile plus 1.5 times the interquartile range or below the first quartile minus 1.5 times the interquartile range.¹⁷

Statistical analysis

We conducted an a priori power analysis using G*Power version 3.1.9.7 to determine the minimum sample size required to test the study hypothesis.¹⁸ Results indicated that a sample size of N=12 was needed to achieve 80% power for detecting a medium effect in a repeated measures ANOVA, with a significance criterion of $\alpha=.05$. We checked normality using the Shapiro-Wilk test and Q-Q (quantile) plots, verifying that most points fell within the 95% confidence interval (CI) drawn on the line of expected quantiles. We performed a repeated measures ANOVA to analyze within-subjects effects for the method-environment interaction, followed by post hoc comparisons adjusted using the Holm method, with the significance level set at $\alpha=0.05$. We analyzed the magnitude of differences using absolute mean differences (MD) and standardized mean differences (Cohen's d, reported as effect size [ES]). We determined agreement between indoor and outdoor environments for each method using Bland-Altman plots,

with limits of agreement (LoA) presented as bias $\pm 1.96 \times SD$. We reported absolute reliability using the standard error of measurement (SEM), calculated as $\sqrt{MS_E}$ where MS_E is the mean square error term from the repeated measures ANOVA.¹⁹ We calculated SEM95, which represents the 95% confidence interval for the standard error of measurement, by $SEM \times 1.96$ (the critical Z-score for a 95% confidence level). This allows us to estimate the range within which an individual's true score is likely to fall, accounting for measurement error. For relative reliability, we used the coefficient of variation expressed as a percentage of SEM (CV%), the intraclass correlation coefficient (ICC), and their CIs. We calculated ICC estimates and their 95% CIs based on the mean score ($k=4$), absolute agreement, and the two-way random effects model. We also report the within-subject standard deviation (s_w) for each setting as a measure of repeatability.²⁰ We performed all statistical analyses using JASP open-source software (JASP Team, 2024).

Results

Cyclists rode at an average speed of 40.7 ± 2.6 km/h across all trials, with a slight variation between outdoor (40.9 ± 2.5 km/h) and indoor (40.5 ± 2.6 km/h) environments ($p < 0.001$). The average power output was 249 ± 45 W, with cyclists producing slightly higher power outdoors (253 ± 44 W) compared to indoors (246 ± 46 W) ($p < 0.001$).

C_DA was lower in the outdoor environment (Notio = 0.251 m², Martin = 0.242 m²), compared to the indoor environment (Notio = 0.252 m², Martin = 0.248 m²) as shown in Figure 1. We found significant differences for Martin ($p < 0.001$, ES = 0.477 , MD = 0.006 , CI95: 0.002 to 0.010), but not for Notio ($p = 0.569$, ES = 0.058 , MD = 0.001 , CI95: -0.003 to 0.005). Both Notio and Martin showed significant differences between the basal and wheels setting in both indoor and outdoor environments: Notio indoor ($p < 0.01$), Notio outdoor ($p < 0.01$), Martin indoor ($p < 0.05$), and Martin outdoor ($p < 0.05$).

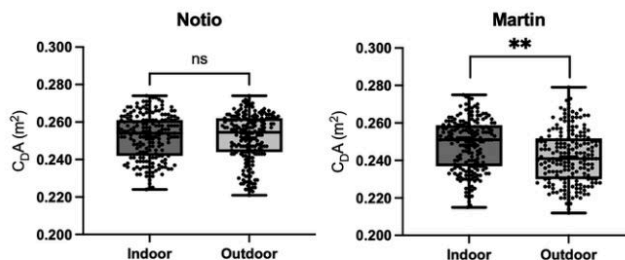


Figure 1. Comparative boxplot between indoor and outdoor coefficient of drag area (C_DA), including medians, interquartile ranges, and outliers, with statistical significance analysis: ns, non-significant; **, $p < 0.01$. Created with GraphPad Prism 10.

Figure 2 illustrates the agreement between indoor and outdoor measurements for both methods. Notio showed a low bias (0.001) with a standard deviation of ± 0.005 , while Martin displayed a slightly higher bias (0.006) with a standard deviation of ± 0.009 . The limits of agreement for Notio (lower = -0.010 and upper = 0.011) and Martin (lower = -0.011 and upper = 0.023) indicate that most differences fall within these ranges, suggesting acceptable agreement between measurements. Both methods show evenly distributed differences in relation to C_{DA} magnitude, although for Notio, the most extreme differences occur at lower C_{DA} values.

Table 1 summarizes the individual average C_{DA} and average within-subject standard deviation (s_w) calculated for each setting. The s_w ranges were as follows: for Notio indoor 0.002 – 0.007 m^2 , for Notio outdoor 0.001 – 0.008 m^2 , for Martin indoor 0.001 – 0.008 m^2 and for Martin outdoor 0.002 – 0.013 m^2 .

Relative reliability for Notio indoor was: $\%CV = 1.66$, $ICC = 0.79$ and $95\%CI$: $[0.64-0.88]$ while for Notio outdoor was: $\%CV = 1.31$, $ICC = 0.89$ and $95\%CI$: $[0.79-0.94]$. Martin indoor showed $\%CV = 1.85$, $ICC = 0.82$ and $95\%CI$: $[0.68-0.89]$ and Martin outdoor: $\%CV = 2.57$, $ICC = 0.72$ and $95\%CI$: $[0.58-0.82]$. Regarding absolute reliability, Notio indoor showed SEM of ± 0.004 m^2 and SEM95 of ± 0.008 m^2 , while Notio outdoor had SEM of ± 0.003 m^2 and SEM95 of ± 0.006 m^2 . For Martin indoor, SEM was ± 0.005 m^2 and SEM95 was ± 0.009 m^2 , while Martin outdoor had SEM of ± 0.006 m^2 and SEM95 of ± 0.012 m^2 .

Average C_{DA} for each setting with CI of SEM95 is shown in Figure 3.

Discussion

This study compared C_{DA} calculations in cycling across indoor and outdoor environments using Notio and Martin methods. Our objectives were to determine if C_{DA} values are consistent regardless of the testing environment, and to assess the practical usefulness of both methods for selecting

the most aerodynamic equipment. Our analysis revealed distinct outcomes for Notio and Martin methods. Notio showed no significant differences between environments, with a minimal variation of 0.001 m^2 (0.4% higher indoor). In contrast, Martin demonstrated a more pronounced difference of 0.006 m^2 (2.4% higher indoor), which was statistically significant. These contrasting results warrant examination of the methodological differences.

Notio, to our knowledge, uses the same formula to calculate C_{DA} both indoors and outdoors. However, Martin incorporates an adaptation in its indoor variant to adjust for cyclist's travel speed.⁵ This adaptation, intended to represent cycling track conditions accurately, may contribute to the observed discrepancy.

The practical utility of absolute C_{DA} values has limitations. In predicting race times or target power, even with accurate C_{DA} data, the variability in outdoor conditions - influenced by buildings, competitors, vehicles, obstacles, and changing atmospheric conditions - makes anticipating exact flow conditions challenging. Consequently, aerodynamic resistance from a tested setup may vary under different flow situations.⁴ Furthermore, when comparing data with scientific literature, different C_{DA} calculation methodologies can yield varying results for identical settings under the same conditions.²¹

Regarding the practical usefulness of both methods for selecting the most aerodynamic equipment, our reliability data based on SEM95, as illustrated in Figure 3, reveals limitations in both Notio and Martin methods across indoor and outdoor environments. Neither system demonstrated the ability to detect real changes in C_{DA} for different equipment settings, as the observed C_{DA} changes were smaller than the range established by SEM95. Despite the Notio method's unique feature of a Pitot-static tube for measuring actual wind experienced by the cyclist, it did not show a significant advantage in detecting small aerodynamic changes. These results suggest that the current sensitivity of both methods may be insufficient for reliably distinguishing between subtle aerodynamic improvements in equipment, regardless of the testing environment.

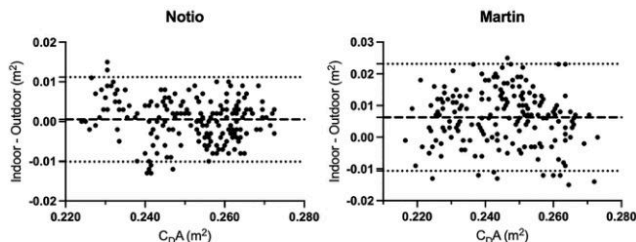
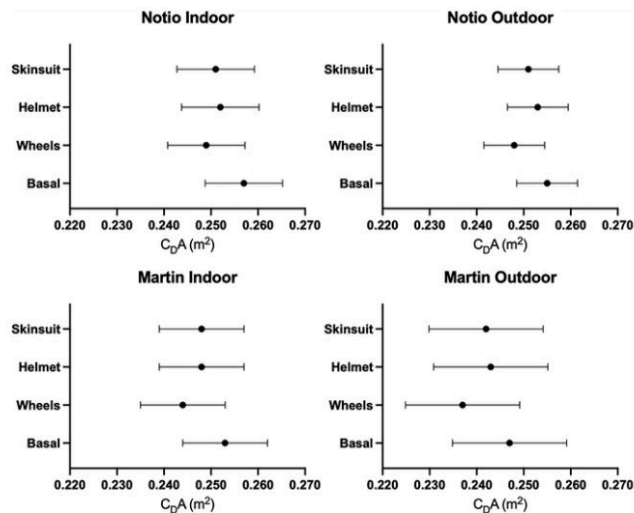


Figure 2. Bland-Altman plot representing the agreement between indoor and outdoor coefficient of drag area (C_{DA}). Created with GraphPad Prism 10.

Table 1. Analysis for each cyclist of mean of coefficient of drag area (C_{DA}) and mean of standard deviation within subject (s_w) calculated for each setting. Data in m^2 .

Cyclist	Notio				Martin			
	Indoor		Outdoor		Indoor		Outdoor	
	C_{DA}	s_w	C_{DA}	s_w	C_{DA}	s_w	C_{DA}	s_w
1	0.236	0.004	0.233	0.004	0.233	0.003	0.224	0.005
2	0.255	0.005	0.253	0.004	0.255	0.004	0.244	0.007
3	0.246	0.004	0.245	0.003	0.238	0.004	0.231	0.007
4	0.232	0.003	0.226	0.002	0.223	0.003	0.224	0.003
5	0.262	0.003	0.258	0.002	0.259	0.004	0.259	0.004
6	0.257	0.003	0.258	0.002	0.255	0.004	0.245	0.004
7	0.240	0.003	0.247	0.003	0.237	0.005	0.235	0.006
8	0.265	0.002	0.266	0.003	0.263	0.005	0.260	0.006
9	0.260	0.003	0.261	0.002	0.256	0.006	0.251	0.008
10	0.249	0.002	0.247	0.002	0.243	0.004	0.238	0.003
11	0.265	0.002	0.265	0.002	0.262	0.002	0.256	0.005
12	0.259	0.003	0.262	0.003	0.256	0.003	0.237	0.004
Average	0.252	0.003	0.252	0.003	0.246	0.004	0.242	0.005

C_{DA} : coefficient of drag area; s_w : mean of standard deviation within subject-within setting.

**Figure 3.** Mean of coefficient of drag area (C_{DA}) for each setting with 95% confidence interval of standard error of measurement (SEM95). Created with GraphPad Prism 10.

Several factors may have contributed to the limited practical utility of both methods. In the indoor environment, riding on a cycling track presents technical challenges. Cyclists must maintain a consistent position while staying above the track's black line, engaging in constant interaction with the track's changing geometry. This requires

continuous adjustments in incline, speed, cadence, and power output.²² Such adaptations can compromise measurement reliability across repeated attempts, potentially masking small aerodynamic improvements.

For outdoor environments, accurately incorporating the actual wind experienced by the cyclist in the C_{DA}

calculation formula is challenging. Our results show Notio achieved a lower SEM value outdoors compared to indoors, suggesting its Pitot-static tube might have contributed to reduced variability between attempts by measuring wind directly. In contrast, Martin exhibited a higher SEM value outdoors. This discrepancy could be due to the inability to incorporate wind into the calculation when intensity drops below the anemometer's threshold. Furthermore, it's critical to recognize that wind encountered by a cyclist along the course may differ from that measured at a single point along the route.

Another factor affecting reliability both indoors and outdoors is the possible involuntary changes in cyclist position. Although the aerodynamic position adopted in this study limits hip and elbow joint mobility compared to upright positions, even small postural changes can lead to notable variations in C_{DA} , as the cyclist's body is the primary contributor to total aerodynamic resistance.²¹ Crouch et al.²³ demonstrated that even in highly controlled wind tunnel tests, this variability persists. They reported variations in C_{DA} measurements for seated positions on the order of 0.001 m^2 , attributed to the difficulty in maintaining and reproducing precise body positions, and sampling errors associated with time-averaged force measurements of fluctuating forces. Notably, they found that small changes in the upper body position, particularly in head height and torso angle, could significantly impact C_{DA} measurements. While Crouch et al.²³ used image analysis to assess position consistency post-hoc, they didn't provide real-time feedback to cyclists during tests. However, wind tunnel facilities have the potential advantage of using video systems for immediate feedback, potentially improving position replication. This capability is unavailable in field testing, which may contribute to greater variability. Despite the controlled environment of wind tunnels, replicability remained challenging, underscoring the inherent difficulties in achieving consistent C_{DA} measurements across repeated trials. These challenges are likely amplified in field testing, where additional environmental factors introduce further variability.

These observations are supported by Merkes et al.,²⁴ who conducted outdoor field tests to measure C_{DA} in different cycling sprint positions. They reported high CV for the same position, ranging from 9.1% to 16.0%. This variability was attributed to cyclists' ability to maintain a stable position and inherent variability in outdoor conditions. They noted that even with a week of training and a familiarization session, achieving reliable C_{DA} measurements in sprint positions remained challenging. These findings highlight the increased complexity of field testing and emphasize the need for caution when interpreting C_{DA} measurements obtained in cycling outdoor environments.

Power is a crucial variable in C_{DA} calculation. The absolute reliability of the powermeter used in this study could be $\pm 6.4 \text{ W}$,²⁵ which according to our calculations based on

Martin's formula, could result in a C_{DA} variability of $\pm 0.006 \text{ m}^2$. Other studies of common cycling powermeters report CV reliabilities between 0.4 and 3%,^{26,27} which can translate into power variability close to that of the power duo mentioned above. These variations must be considered when interpreting C_{DA} results calculated from power measurements.

Although to a lesser extent, another factor influencing C_{DA} calculation reliability is the accuracy of the meteorological station in determining air density. In our outdoor measurements, we observed air density changes up to 3% throughout the protocol with the same cyclist, primarily due to temperature variations. Underwood⁷ reported a 0.4% uncertainty in air density calculation under specific conditions (20°C , 1000 Pa), which, according to our calculations based on Martin's formula, could translate to an approximate C_{DA} variation of 0.001 m^2 .

Kordi et al.¹¹ analyzed Notio's performance in an indoor velodrome setting. Their s_w data for the same position ranged from 0.001 to 0.003 m^2 , better than our range of 0.002 to 0.005 m^2 . It is important to note that even their smallest error of 0.001 m^2 can significantly impact performance. The differences between our data and theirs can be attributed to factors including power measurement unit reliability and body position consistency. Their study sample consisted of elite track cyclists, which likely favored accurate position replication on each attempt.

Valenzuela et al.¹³ also tested Notio's performance indoors. Their s_w data was 0.015 m^2 , three times higher than our highest average value and five times higher than Kordi et al.'s¹¹ highest value. This high value significantly limits the system's ability to detect real C_{DA} changes between settings. They used a Cycle Ops PPI powermeter, with a CV between 1.6 to 3.7%.²⁷ Their sample consisted of trained, but not elite cyclists, likely challenging position replication across trials. They tested three settings, including an upright position, allowing greater elbow and hip joint movement, increasing difficulty in replicating the exact position.

They concluded that while Notio could detect large changes in C_{DA} (such as between upright and aerodynamic positions), it was not sensitive enough to detect smaller changes (like switching helmets). This aligns with our observations about the system's limitations in detecting subtle C_{DA} variations. These findings highlight the importance of considering the level of precision required when using such systems for aerodynamic optimization in cycling.

In modern competitive cycling, victories are often decided by seconds. Even a small C_{DA} change of 0.001 m^2 can significantly impact performance, especially at higher speeds where aerodynamic resistance is paramount. This underscores the importance of accurately measuring minor C_{DA} differences. To contextualize such a small change, consider the 2024 Giro d'Italia. Tadej

Pogačar completed the 40.6 km time trial at 47.1 km/h average speed to secure victory. Our calculations using Martin's formula show that a 0.001 m^2 C_{DA} improvement could result in an 11-s time advantage. Given that many Grand Tour time trials are won by seconds, such an improvement could determine stage wins or overall race outcomes. This example illustrates why reliably detecting and measuring small C_{DA} changes is crucial for optimizing cycling performance at the highest levels of competition.

Our study has several limitations. The first is related to the C_{rr} value. Although the riding surface was different between indoor and outdoor, we used the same C_{rr} values, which could have affected the result in the comparison of the absolute C_{DA} value. Regarding the outdoor wind measurement, we were unable to measure constant wind, only some wind gusts at specific moments, so we did not incorporate wind into the C_{DA} calculation using Martín's method. Furthermore, we measured the wind only at one point along the course, so even though the cyclist may have encountered wind at some point during the ride, this was disregarded.

Our findings highlight the importance of understanding the limitations of field-based C_{DA} calculation methods, particularly their limited sensitivity to detect small changes in C_{DA} . Given that procedure is subject to error, we recommend conducting a protocol of repeated measures for each tested setting, reporting average C_{DA} values with s_w to enable predictions and comparisons based on this range. This approach acknowledges the inherent variability in measurements and provides a more realistic context for interpreting results.

On the other hand, powermeter error is a significant concern in these tests. We encourage evaluating power sensor reliability beforehand to interpret its impact on C_{DA} calculations. Although field tests provide realistic conditions, cumulative errors could exceed C_{DA} changes from equipment or position modifications, needing careful result interpretation.

Initial disappointing results should not discourage these methods' adoption. Understanding potential error sources can improve testing conditions and establish a clear range of detectable C_{DA} changes, optimizing time and resources, while recognizing the limitations.

Conclusions

This study demonstrates that while Notio calculates C_{DA} consistently across indoor and outdoor environments, Martin shows significant differences between them. However, neither method exhibited sufficient sensitivity to detect meaningful changes in C_{DA} across different equipment settings in either environment. The SEM95 exceeded the observed C_{DA} changes for all settings relative to the baseline, regardless of environment. These findings underscore the challenges in obtaining reliable C_{DA}

measurements in field conditions, even with advanced devices like Notio. The results highlight the current limitations of these field-based methods in accurately quantifying small aerodynamic differences that could be significant in competitive cycling.

Statements and declarations

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Data availability statement

All raw data files are available on OSF via doi:

The data that support the findings of this study are openly available in figshare at <http://dx.doi.org/10.6084/m9.figshare.26015878>

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