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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_DA 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_DA 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_DA 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.

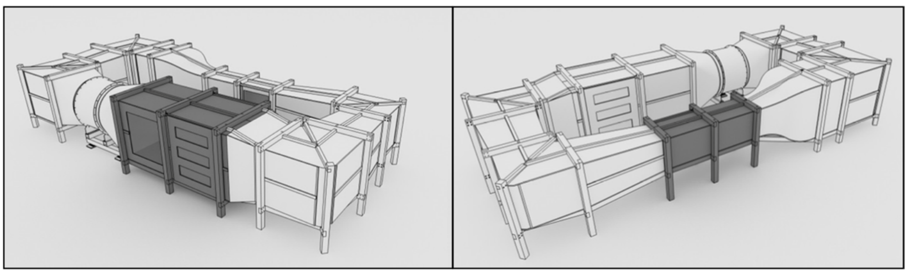

Figure 1. Three-dimensional representation of the wind tunnel, with the two test sections shaded, the low-speed test section on the left and the high-speed test section on the right. Original image of the wind tunnel manual with permission (Oritia & Boreas).

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 ±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.

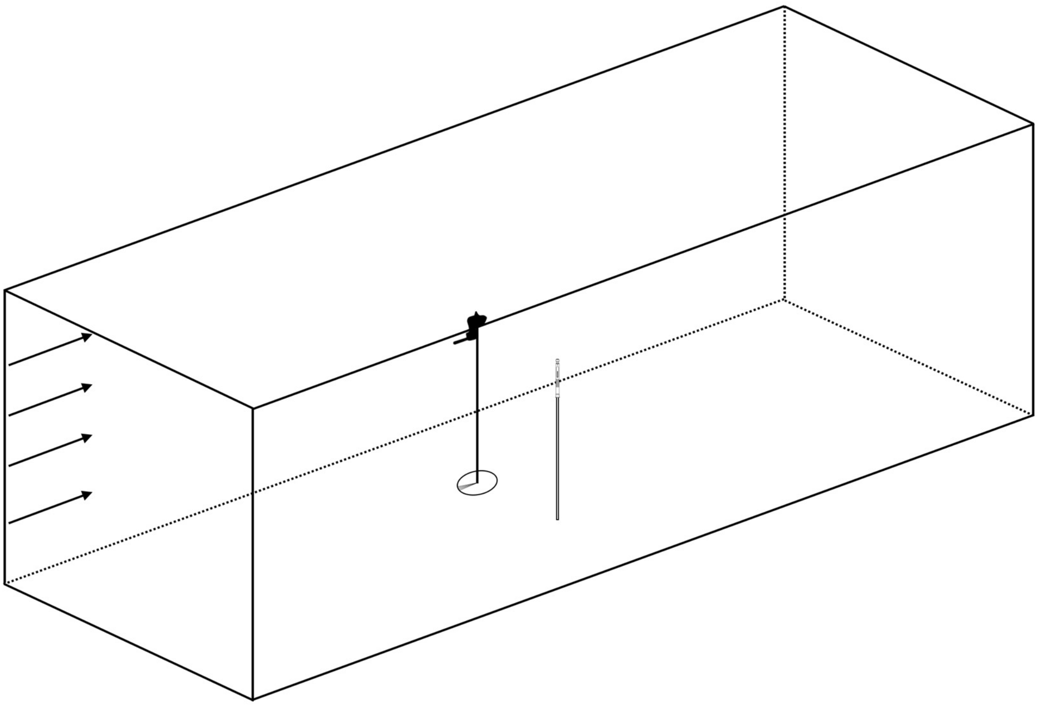

Figure 3. Scaled graphical representation of the arrangement of Notio and hot-wire anemometer in the high-speed test section of the wind tunnel.

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:

$$q = \mathrm{P}_0 - \mathrm{P}_s \tag{1}$$

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:

$$q = \frac{1}{2}\,\rho\, U_\infty^2 \tag{2}$$

and resolve it as follows:

$$U_\infty = \sqrt{\frac{2\,q}{\rho}} \tag{3}$$

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 ± 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 $\pm 1.96 \times$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).

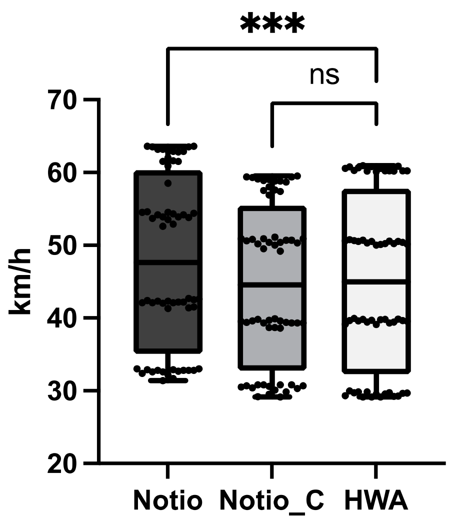

Figure 4. Comparative boxplot between Notio, Notio_C, and HWA wind speed (WS), including medians, interquartile ranges, and outliers, with statistical significance analysis: ns, non-significant; *** $p < 0.001$. Created with GraphPad Prism 10.

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 ± SD	**Mean ± SD**	***p*-Value**	**ES**	**Mean ± SD**	***p*-Value**	**ES**
Fan Power (%)	21%	29.52 ± 0.29	32.57 ± 0.47	<0.001 ***	5.65	30.28 ± 0.59	0.101	1.41
	28%	39.59 ± 0.25	42.11 ± 0.42	<0.001 ***	4.68	39.34 ± 0.40	1.000	−0.46
	37%	50.42 ± 0.23	54.23 ± 1.31	<0.001 ***	7.06	50.44 ± 0.54	1.000	0.04
	44%	60.45 ± 0.29	62.65 ± 0.90	<0.001 ***	4.06	58.55 ± 0.85	<0.001 ***	−3.52
Yaw Angle (°)	0°	44.94 ± 12.09	47.68 ± 11.88	<0.001 ***	5.06	44.37 ± 11.38	1.000	−1.06
	5°	45.20 ± 12.22	47.78 ± 11.67	<0.001 ***	4.77	44.66 ± 10.90	1.000	−1.01
	10°	44.94 ± 12.06	48.69 ± 12.41	<0.001 ***	6.94	45.19 ± 11.37	1.000	0.47
	15°	44.95 ± 12.08	48.03 ± 12.08	<0.001 ***	5.70	44.87 ± 11.30	1.000	−0.15
	20°	44.95 ± 12.09	47.28 ± 11.94	<0.001 ***	4.33	44.18 ± 11.20	0.825	−1.41

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.

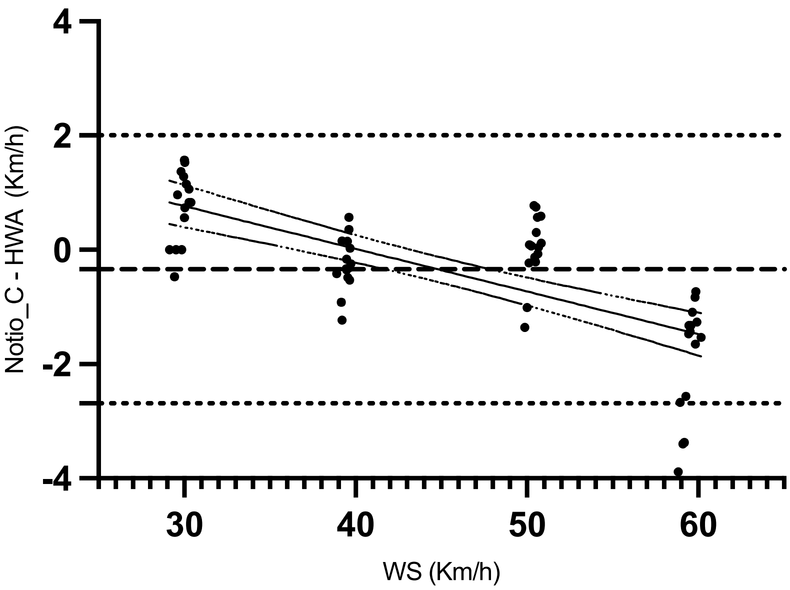

Figure 5. Agreement between Notio_C and HWA wind speed (WS) Bland–Altman plot. Created with GraphPad Prism 10.

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_DA 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 m^2 in C_DA. In a 40 km individual time trial, this discrepancy in C_DA 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_DA calculation formula. However, small errors can impact in the practical field of aerodynamic evaluation. Furthermore, the absence of information on the C_DA 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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Data Availability Statement: Due to the particularity of the wind speed calculation process at the wind tunnel, different from the usual use of Notio, and which required a development application provided by the manufacturer, a confidentiality agreement was required for the raw data.

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Conflicts of Interest: The authors declare no conflicts of interest.

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