Development and validation of a low- cost system for assessing aerodynamics in cycling using computational fluid dynamics

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Abstract

Introduction: *The purpose of this study was to develop and validate a low- cost system for assessing aerodynamics in cycling using computational fluid dynamics (CFD). This was necessary since there isn't an alternative, for assessing aerodynamics, available for bike fitters who don't have access to a wind tunnel.* ***Method***: *A low- cost 3D scanning system had to be developed. One elite cyclist had to perform 3 trials in 3 different positions on the 3D scanning system followed by CFD simulations, and the same 9 trials in a wind tunnel for validation purposes. During all trials, the drag coefficient was being examined.* ***Results***: *The average accuracy of the system was 91.8% compared to wind tunnel tests. The precision of the system, aka the repeatability of the trials, was 94.8% compared to 97.5% from wind tunnel tests.* ***Conclusion***: *These results show the potential of the system as an alternative for wind tunnel tests when it comes to assessing aerodynamic performance in cycling. Considering the possibilities on further improvements, it should be able to obtain even better results with this system.*

KEY WORDS: Aerodynamics, 3D Scanning, Computational Fluid Dynamics, Wind tunnel, Cycling.

Introduction

In the last few years increasing attention in the cycling sport has been placed on coaching and supervision of the cyclist. Considerable progress has been made, particularly in the field of training and nutrition, that the physical performance has nearly reached its optimum. In order to further improve the efficiency of the cycling movement, optimizing the position on the bicycle is an absolute prerequisite (bikefitting, n.d.).

Therefore, the ultimate aim for bike fitters is to find a cycling position which is as efficient and as aerodynamic as possible. The efficiency can be measured through the intake of oxygen, or determined by the cost function based on the moments in the joints during the cycling movement. The golden standard for analyzing aerodynamics in cycling is with wind tunnel tests (Bini and Capres, 2014). However, not many bike fitters have access to a wind tunnel or an alternative, like field tests in a velodrome (Bouillod et al., 2016), and therefore have no accurate method for assessing aerodynamics. This is unfortunate, since aerodynamics has a big influence on cyclists. For instance, at racing speeds (± 50 km/h), the aerodynamic resistance experienced by a cyclist, also called drag, is about 90% of his total resistance (Grappe et al., 1997; Kyle and Burke, 1984). Meaning, aerodynamic improvements, particularly on flat rolling terrain, offer the greatest potential for improvements in cycling speed (Wilson and Papadopoulos, 2004). This is also proven by Oggiano et al., (2008), who showed that the cyclist's position has a significant impact in the performance on flat terrain to overcome at the maximum air resistance. Oggiano et al. (2008) and Blocken et al. (2013) showed that the body of the cyclist accounts for roughly 70% of the total drag, while the remaining 30% is due to the bicycle frame and the components. Therefore, it can be stated that optimizing the cycling position is of main importance for improving aerodynamics and minimizing the metabolic cost of cycling.

In order to include aerodynamics in bike fitting, a good alternative for wind tunnel tests has to be found. According to Defraeye et al. (2010b), Computational Fluid Dynamics (CFD) might be an attractive alternative compared to expensive and time- consuming wind tunnel assessments. Encouraging results, from CFD simulations applied to cycling, support this suggestion (Bouillod et al., 2016; Defraeye et al., 2010a; Defraeye et al., 2010b; Defraeye et al., 2011; Lukes et al., 2002; Oggiano et al., 2015; Mannion et al., 2016). A few of these studies validated the use of 3D scanning combined with CFD.

Bouillod et al. (2016), Oggiano et al. (2015) and Defraeye et al. (2010a) did assess/determine the frontal area combined with the drag coefficient of a cyclist, while Defraeye et al. also looked at the performance of different turbulence modelling (2010b) and drag and convective heat transfer of body segments (2011). However, in each of these studies scanners of more than €11.000 were used. This may not be considered a realistic option for assessing aerodynamic performance for bike fitters. Nevertheless, the results of these studies were very promising, showing that combined 3D scanning and CFD simulations were in accordance with wind tunnel measurements with an accuracy of approximately 90%. The accuracy is lower due to the main issue that, in order to reduce the computational cost of the simulations, turbulence has to be modelled and cannot be fully resolved. However, this deviation in accuracy seems to be constant across different measurements, resulting in a high relative accuracy.

At this moment, no commercial 3D scanning system including CFD simulations is available for bike fitters. Therefore, the purpose of this study was to develop and validate a low-cost system for assessing aerodynamics in cycling using CFD simulations.

Method

Subject

One elite male cyclist without neurological or physical impairments (height 184 cm; mass 71 kg) volunteered to participate in this study. Prior the testing he received a full explanation of the nature and purpose of the study. The subject performed two testing sessions with the same road- racing bicycle; 3D scanning with CFD (3D-T) and wind tunnel test (WT-T).

Development of the 3D Scanning System

Since the low- cost system for assessing aerodynamic performance in cycling is meant to serve as a measurement device for bike fitters, some specifications had to be met. The most important specifications were that: 1) The time span from scanning the cyclist until the import of the 3D scan into the virtual wind tunnel had to be less then 10 minutes, since a bike fitting normally doesn't take more than 2 hours. 2) The scanning device had to have a high spatial resolution (minimum of 1 mm in all dimensions). 3) The total manufacturing costs of the system had to remain below €500, since it had to be affordable for bike fitters. By these considerations, a lot of potential 3D scanners were excluded (mainly due to the specification to be low cost), resulting in the Xbox Kinect 360 as best option for this system.

The resolution of a Kinect fits the constituted specifications, and provides the possibility to combine multiple Kinects for capturing a larger surface. Furthermore, purchasing multiple Kinects (including adapters) was well within budget. The main reason for preferring the Xbox Kinect 360 above the follow up model (Xbox Kinect One), despite the higher accuracy of the Xbox Kinect One, was that the Xbox Kinect One has the limitation that it did not allow for connecting multiple Kinects to a single workstation.

Figure 1. The scanning device (left). The rotation platform (right).

To perform a full body scan, the cyclist had to be rotated. For this reason, a rotation platform has been developed. The most important terms that had to be met were: 1) The platform had to be able to make a full rotation in 60-90 seconds. 2) It should be possible to place a race bike without wheels on the platform. 3) The platform should be able to hold a load of approximately 110 kg. 4) Together with the scanning device, the costs should be under €500. These terms have all been met, resulting in the setup shown in Figure 1.

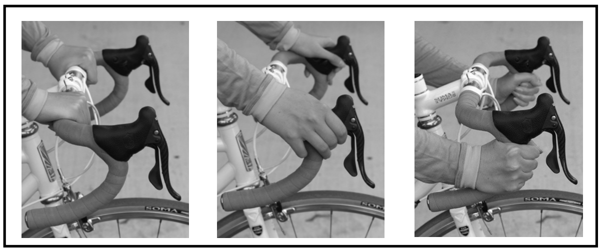

Figure 2. The three different positions of the hands. From left to right: hands on tops (HT), hands on hoods (HH), hand on drops (HD).

3D Scanning with CFD

The participant had to perform a total of 18 trials. The position on the bike varied between: hands on hoods (HH), hands on tops (HT) and hand on drops (HD) (Figure 2). The placement of the hands was predefined by tape on the handlebar. During 3D-T, the subject had to maintain in these three positions while he was scanned three times in each position, with no allowed movement between trials. These tests were done to determine the precision (repeatability) of the system. During all trials, the crank arms had to remain horizontal. This was checked by using a level on the crank arm.

Figure 3. A 3D scan made of the cyclist

After the 3D scanning was done, and the scans of the Kinects were to be aligned, the resulting 3D mesh (Figure 3) was exported for CFD simulations in a virtual wind tunnel. The meshes of the 3D scans varied between 1.56 million and 1.77 million cells. The numerical wind tunnel consisted of a box with a cross section of 6x6 m^2 and a total length of 21 m (Blocken et al., 2013; Figure 4). The cyclist was placed at 3 m from the inlet and in the center of the test section. A finer mesh (5.12 million cells) from the cyclist was used in a preliminary test in order to ensure a grid independence solution. In both 3D-T and WT-T, the drag force (F_d) was analyzed.

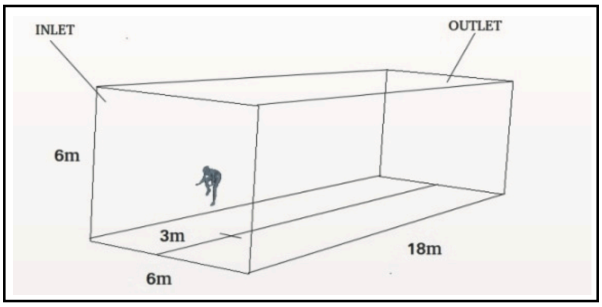

Figure 4. Numerical wind tunnel.

Wind Tunnel Test

A to the project independent wind tunnel was used to measure F_d. It was an open circuit wind tunnel with a length of ~50 m (figure 5). The testing section was 2.5 m wide, 2.5 m high and 6.5 m long (Flanders' BikeValley, Beringen, Belgium). The mean velocity variation over a length of 1.5 m had an average variation of 0.6% which means that the variation of velocity along this test section is very low i.e. uniform flow is observed. The turbulence level in the test section was approximately constant and equal to 1.14% which is accepted as a good value for a full-scale wind tunnel. The mean deviation of the drag coefficient from a standardized curve was equal to 0.03, which proves the accuracy of the wind tunnel (Viswanathan and Van Riet). The subject had to perform a total of 9 trials (WT-T), the same way as with 3D-T.

Data Registration and Analysis

Four Xbox Kinect 360's with adapters were used for 3D scanning. The Xbox Kinect 360 has a resolution of 0.051 mm, and the KSCAN3D software (LMI Technologies, Vancouver, Canada) made it possible to combine multiple Kinects for capturing a larger surface. The measurements in the wind tunnel were recorded over 30 seconds once the wind speed was stabilized after 30 seconds (Garcia-Lopez et al., 2008). The F_d was determined right away. The CFD simulations were performed with Flow Design software (Autodesk, Mill Valley, USA). Turbulence was solved by using a(n) (unsteady) Smagorinsky Large Eddy Simulation (LES) model. Defraeye et al. (2010a) show that LES is found to provide more accurate flow predications then a (steady) Reynolds-averaged Navier- Stokes (RANS).

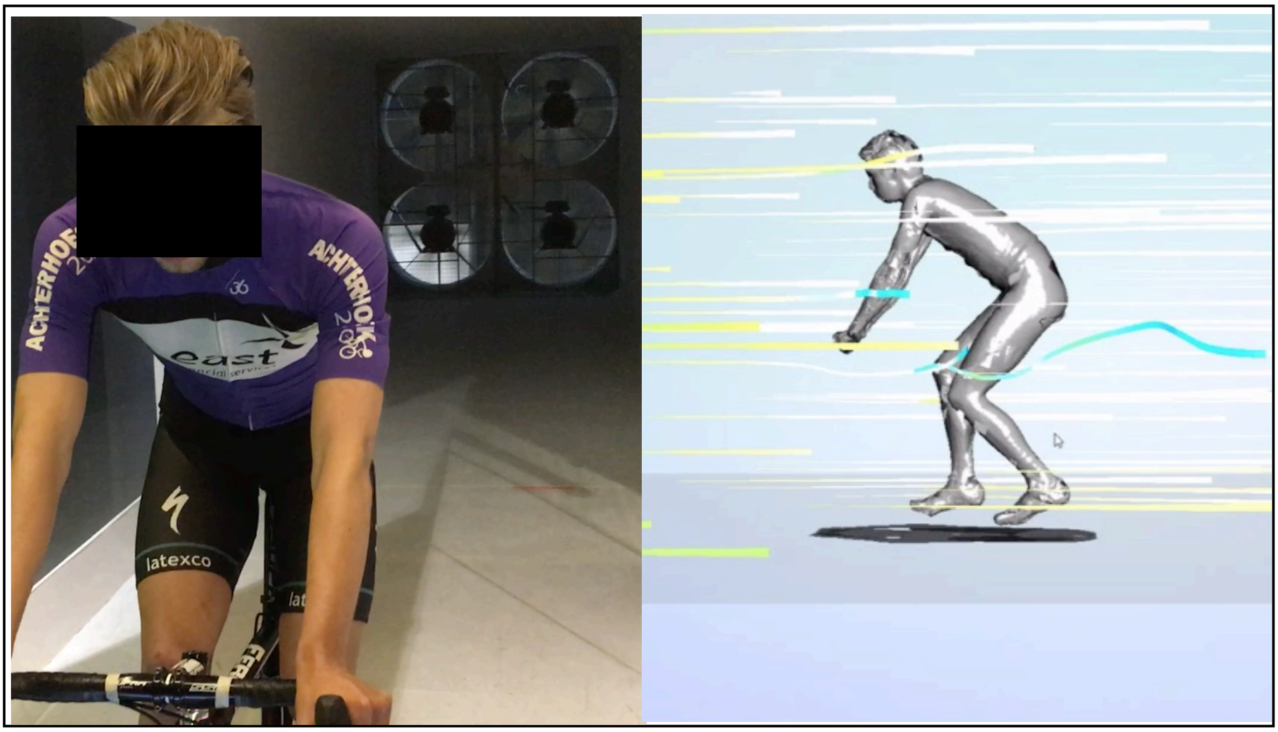

Figure 5. The cyclist in the wind tunnel (left). A 3D scan of the cyclist in a virtual wind tunnel (right).

A validation study showed that Flow Design was able to predict wind tunnel results of the average F_d within 6% accuracy (Autodesk Flow Design, 2014). When the status of the model changed from transient to stabilized, the flow reached a steady- state condition and was no longer changing. The F_d could then be determined.

The F_d was calculated for 3D-T and WT-T at a velocity of 10.4 m/s, 14.4 m/s and 18.7 m/s. The F_d obtained from equal positions were compared to determine the precision of the 3D scanning system. Furthermore, the F_d obtained from equal positions were compared between the results of 3D-T and WT-T to determine the accuracy of the 3D scanning system. The coefficient of variation (CV) has been calculated for the F_d of each equal position, in the same test settings, as the ratio standard deviation (σ) to the mean (μ) (Hopkins, 2000).

$$(1)\ CV = \frac{\sigma}{\mu} \cdot 100$$

The lower the CV, the smaller the residuals relative to the obtained value (Gomez and Gomez, 1984; Steel and Torrie, 1980).

Results

The F_d of the cyclist was assessed by combining 3D scanning and CFD simulations. The results were compared with the F_d obtained from the wind tunnel tests.

The data presented in table 1 shows F_d as mean value (±S.D.) together with the coefficient of variation. Figure 6 shows the F_d obtained from 3D-T and WT-T as mean values.

	HT (10.4)	HT (14.4)	HT (18.7)	HH (10.4)	HH (14.4)	HH (18.7)	HD (10.4)	HD (14.4)	HD (18.7)
3D-T - F_d	16.00±1.41	30.60±2.55	53.80±0.85	16.35±1.06	31.20±2.26	54.75±1.91	14.50±0.46	27.57±1.00	46.27±1.63
CV (%)	8.8	8.3	1.6	6.5	7.2	3.5	3.2	3.6	3.5
WT-T - F_d	18.65±0.35	35.90±0.14	57.20±3.39	17.55±0.07	33.65±0.07	56.40±2.4	15.50±0.14	30.50±0.57	48.40±3.39
CV (%)	1.9	0.4	5.9	0.4	0.2	4.3	0.9	1.9	7.0
DIF - F_d	2.65	5.30	3.40	1.20	2.45	1.65	1.00	2.93	2.13

Table 1. The drag forces presented as mean value (±S.D.). 3D-T - F_d: Drag forces (N) obtained from the 3D scanning combined with CFD; WT-T – F_d: Drag forces obtained from wind tunnel tests. Coefficients of Variation (CV's) have been determined for both 3D-T – F_d and WT-T – F_d; DIF – F_d: Difference in drag forces (N) between 3D-T and WT-T.

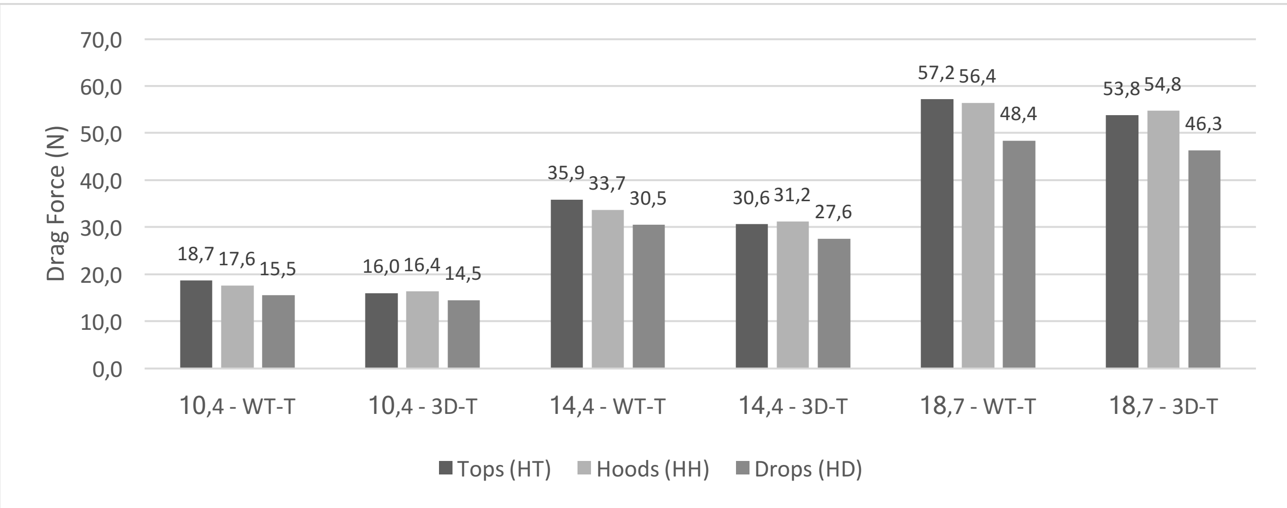

Figure 6. The drag forces presented as mean value in three positions, for both WT-T and 3D-T tests at three different velocities. Positions: Hand on Tops (HT), Hands on Hoods (HH) and Hands on Drops (HD); Different velocities: 10.4 m/s, 14.4 m/s and 18.7 m/s; WT-T: Wind tunnel tests; 3D-T: tests with 3D scanning and CFD.

Discussion

System Specifications

As mentioned earlier, specifications for the low- cost system for assessing aerodynamic performance in cycling have to be met. The main terms are evaluated here. The first term is that the time span from scanning the cyclist until the import of the 3D scan into the virtual wind tunnel should be less then 10 minutes. The 3D scanning of the cyclist is done in less than one minute. The aligning of the scans takes about 4 minutes, while the combining and finalizing takes roughly 5 minutes. This is just within the term that is set. However, unneeded points have to be deleted from the meshes as well, which takes about 5 minutes since the bike had to be removed to. Without the removal of the bike this term will be met. Furthermore, the processing time can be shortened with a faster workstation.

The second term states that the scanning device must have a high resolution (minimum of 1 mm). Since the resolution of the Xbox Kinect 360 is 0.051 mm, this term is also met. The last main term is that the manufacturing costs for the system must remain below €500 since it has to be affordable for bike fitters. The rotation platform costs €340, while the scanning device costs €166. This means the total manufacturing costs for the system are €506, and therefore just exceeds the term. However, the price can be reduced when the system is produced on a larger scale; the shipping costs of the parts will be lower, as well as the price. Looking at the evaluation of these terms, it can be stated that the system has potential as an alternative for wind tunnel tests when it comes to assessing aerodynamic performance in cycling.

Accurcy and Precision

Within this study the accuracy and precision of the 3D scanning system was investigated. The accuracy was determined by comparing the results from three different positions between 3D-T and WT-T, while the precision is analyzed by comparing equal positions within 3D-T to determine the repeatability. In this case, the precision is more important than accuracy, as long as the difference between 3D-T and WT-T is relatively the same.

Table 1 shows that for a velocity of 10.4 m/s, the maximum difference in drag force between 3D-T and WT-T is 2.65 N. For a velocity of 14.4 m/s this difference is 5.30 N, while a velocity of 18.7 m/s leads to a variety of 3.40 N. A side note to these results is that the standard deviation of WT-T increases at higher velocities. The average difference in drag force, for all the trials together, between 3D-T and WT-T is 2.52 N. As mentioned earlier, only a few other studies have been conducted when it comes to investigating the reliability of CFD simulations on 3D scans of cyclists. Those studies have not looked at the drag force, but Bouillod et al. (2016), Oggiano et al. (2015) and Defraeye et al. (2010a) did asses the frontal area combined with the drag coefficient (AC_d) of a cyclist.

$$(2)\ F_d = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot C_d$$

Formula 1 shows that, since the velocity and the density of the fluid is equal between WT-T and 3D-T, the measured differences for AC_d (expressed in %) are the same for F_d. Bouillod et al. (2016) found that AC_d of computed by CFD simulation predicted AC_d with an accuracy of 89.1%, Oggiano et al. (2015)

found an accuracy of CFD simulations of 90%, while Defraeye et al. (2010a) found an accuracy of 93%. In our case, the F_d computed by CFD simulation is 9.4% lower for 10.4 m/s, 10.7% lower for 14.4 m/s and 4.4% lower for 18.7 m/s. Meaning, the average accuracy of the system, when it comes to determining F_d, is 91.8% compared to wind tunnel tests. These results show good agreement with previous experiments. An accuracy of 91.8% is considered to be a close agreement in CFD studies (Defraeye et al., 2010b).

For the precision, the average coefficients of variation are analyzed. For a velocity of 10.4 m/s the CV for 3D-T is 6.2%, for 14.4 m/s 6.4% and for 10.87 m/s 2.9%. For WT-T the average CVs are respectively 1.1%, 0.8% and 5.7%. Meaning, the average precision for 3D-T is 94.8%, and the average for WT-T is 97.5%. These results show that the wind tunnel is more precise then the 3D scanning combined with CFD. However, during the wind tunnel tests the subject had visual feedback of his position by comparing his current position to his initial position due to a camera on the sagittal plane combined with a projector pointed in front of him. The subject was not given such feedback during the 3D-T, meaning the chance of a(n) (slightly) adjusted position between trials increased.

Previous research by field testing and wind tunnel experiments (Broker, 2003; Garcia-Lopez et al., 2008; Grappe et al., 1997, Jeukendrup and Martin, 2001) showed that adjustments to the cyclist's position, even minor ones, can result in a variation in aerodynamic drag. This indicates that the 3D scanning system may actually be a bit more precise than measured during this study. The results also show that the CV for WT-T at 18.7 m/s is significantly higher than at other velocities. This could (partly) be explained due to the shivering of the subject as a result of the cold wind acting on his skin during the static measurements, supporting the assumption that slight adjustments to the cyclist's position can result in variation in aerodynamic drag.

Limitations and Future Research

KSCAN3D is used to capture and align 3D meshes. Once the data were captured, KSCAN3D is used to delete unneeded points, smooth data, etc. A limitation of KSCAN3D is that the meshing technique was unknown. A different meshing software which uses polyhedral meshing techniques, in case KSCAN3D does not use that technique, may result in smoother surfaces using fewer cells and reducing computational costs. Furthermore, it is not possible to change or check the skewness of the mesh, as well as the smoothness, the aspect ratio of the cells and the boundary layer mesh generation. Future research is required to investigate the effect of these settings on the results. However, when considering alternative software, it should be taken in account that a fast processing is of major importance, since a bike fitting normally does not take much more then approximately 2 hours. Alternative 3D scanners should be considered as well, which would result in more options for meshing software, since the condition that the software should be able to capture multiple Kinects would then expire.

Another limitation is that the bike has to be removed from the 3D scan, which is a time-consuming task. This is done since the 3D scanner couldn't scan reflecting materials properly. Since this system is developed for bike fitters, a bike with easily adjustable parameters will most likely be placed upon the rotation platform. This bike can be made in such a way that it isn't reflective, meaning it can be scanned resulting in a faster process. Since the bike is removed from the 3D scans, it is removed from the wind tunnel tests as well. This is done by measuring the drag force from the bike separately and subtracting it from the results. A limitation to this is that the bike and the rider may influence each other on the findings.

As mentioned earlier, the position between trials varies a bit due to shivering of the subject during WT-T and the lack of visual feedback during 3D-T. A good way to take account for those errors would be to 3D scan a cyclist and print a mannequin of it, which could be used for both tests. Unfortunately, this was impossible for this study due to limited financial resources, but it should be considered for a future study now that the potential of this system is shown.

A general limitation to this system is that no materials are applied to the 3D scan. The current available software does not allow for an easy and fast solution for this problem, so for the moment it seems that there will be a slight difference in results compared to wind tunnel tests. However, as long as the difference is relatively, and similar for each measurement, that is not expected to be a problem.

Conclusion

A low-cost 3D scanning system for assessing aerodynamics in cycling has been developed and validated for this study. The terms for the developing part have mostly been met, while the most important findings of the validation study are: 1) The average accuracy of the system, when it comes to determining F_d, is 91.8% compared to wind tunnel tests. 2) The precision of the system was 94.8%, while the wind tunnel performed at a precision of 97.5%. These results may actually have been better, when the testing would have been done with a mannequin. Nevertheless, these results show the potential of the system as an alternative for wind tunnel tests when it comes to assessing aerodynamic performance in cycling. Considering the possibilities on further improvements, it should be feasible to obtain even better results with this system.

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