



REFERENCE VALUES AND IMPROVEMENT OF AERODYNAMIC DRAG IN PROFESSIONAL CYCLISTS

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ABSTRACT

This study aimed to measure the aerodynamic drag in professional cyclists, to obtain aerodynamic drag reference values in static and effort positions, to improve the cyclists' aerodynamic drag by modifying their position and bicycle equipment, and to evaluate the advantages and disadvantages of these modifications.

The study was carried out in a wind tunnel with five professional cyclists. Four positions were studied with a time-trial bicycle and one position with a standard racing bicycle. In every position the aerodynamic drag and kinematic variables were recorded. Drag area for the time-trial bicycle was 31% higher in effort than in static position, and lower than for the standard racing bicycle. Changes in the cyclists' position decreased the aerodynamic drag by 14%. The aero-helmet was not favourable for all cyclists. The reliability of aerodynamic drag measures in wind tunnel was high ($r > 0.96$, $CV < 2\%$).

In conclusion, we have measured and improved the aerodynamic drag in professional cyclists. Our results were higher than those obtained by other studies that did not assess the aerodynamic drag during effort at race pace and that employed different wheels. The efficiency of the aero-helmet, and the validity, reliability and sensitivity of wind tunnel and aerodynamic field testing were debated.

Introduction

It has been reported that the aerodynamic drag influences cycling performance (Kyle, 1979), especially in individual and team time-trial races (Padilla *et al.*, 2000). The aerodynamic drag is the main resistive force (about 80% of the total resistive force at 30 km·h⁻¹) on level ground (Di Prampero, 2000). The external power required for the cyclist-bicycle system to overcome the aerodynamic drag is a third order polynomial of the system velocity (Swain, 1994), so it is necessary to double the pedaling power in order to increase cycling speed from 32.4 km·h⁻¹ to 43.2 km·h⁻¹ (Grappe *et al.*, 1997). Consequently, if we consider that the cyclist's power is limited, it becomes important to reduce the aerodynamic drag in order to improve cycling performance. One option is to modify the bicycle's dimensions and the cyclist's posture in accordance with the International Cycling Union rules (UCI, 2006). Many cycling world hour records were broken some years ago, when special bicycles were allowed, although these records have since been declared null and void (Basset *et al.*, 1999; Padilla *et al.*, 2000). Nowadays it is possible to use bicycles with an aerodynamic frame, special handlebars and special (lenticular) wheels in order to improve the aerodynamic drag (Jeukendrup and Martin, 2001). These strategies could reduce pedaling power by 60 W at 50 km·h⁻¹ (Menard, 1992). This reduction represents about 12% of the VO_{2max} pedaling power in professional cyclists (Lucia *et al.*, 2000). Aerodynamic drag increases have been reported when cyclists wear standard helmets instead of aero-helmets (Kyle, 1989), which would increase pedaling power to maintain a given velocity by 9-18 W (2-3% of the VO_{2max}). Conversely, this power is reduced (6%) by small changes in cyclists' position (Jeukendrup and Martin, 2001). Different techniques have been used to evaluate the aerodynamic drag in cycling (Grappe *et al.*, 1997; García-López *et al.*, 2002): traction resistance test, lab-to-field extrapolation,

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3 simplified deceleration method, force transducers and wind tunnel. The wind tunnel is
4 the most valid and reliable technique (Hoerner, 1965), because it is sensitive to different
5 types of handlebars, frames and wheels in the same bicycle (Dal Monte *et al.*, 1987;
6 Menard, 1992; Tew and Sayers, 1999). Its main disadvantages are *a) its high cost.*

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10 Therefore, few studies have been carried out with professional road cyclists in a wind
11 tunnel; most aerodynamic drag measurements were obtained using other methods (García-
12 López *et al.*, 2002). *b) Wind-tunnel tests were not performed in actual cycling locomotion.*
13 Only one study (Martin *et al.*, 1998) simulates pedaling (no resistance), in spite of the fact
14 that some authors believe that there are differences between dynamic and static positions
15 (Candau *et al.*, 1999). No other study assessed the aerodynamic drag in a wind tunnel
16 during effort at race pace.
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20 The aims of this study were: a) to measure aerodynamic drag in a representative group
21 of professional cyclists in a wind tunnel, b) to obtain reference values in static and effort
22 (at race pace) positions, c) to improve the cyclists' aerodynamic drag by modifying
23 bicycle position and equipment, and d) to evaluate the advantages and disadvantages of
24 these modifications.
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43 **Methods**

44 *Participants*

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48 Five professional road cyclists (weight: 71.6 ± 2.7 kg and height: 1.79 ± 0.03 m) participated
49 in this study. All of them were healthy males who had been international competitors with
50 the Kelme-Costa Blanca team (age: 22-30 years), and had several years' cycling
51 experience. After the present study, all of them participated in the *Tour de France* and the
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3 *Vuelta a España* 2001 and 2002. The evaluation protocol for sportsmen was designed
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5 according to the Helsinki Conference for research on human beings, and all cyclists signed
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7 their consent before starting the study.
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10 11 12 *Experimental design* 13 14

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17 The cyclists performed five wind-tunnel tests in different positions (Figure 1). The first
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19 four tests (positions 1-4) were carried out with a special time-trial bicycle (model KG
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21 396®, Look SA, France) equipped with an aero-handlebar (model ITM System
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23 Extensions, Italmanubri SA, Italy). The fifth test (position 5) was done with a standard
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25 bicycle (model KG 381®, Look SA, France) equipped with a standard handlebar (model
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27 ITM, Italmanubri SA, Italy). For all five tests the front and rear wheels were standard
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29 wheels (Mavic Open Pro SUP®, Salomon SA, France) with 32 oval spokes (diameter of
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31 1.8 mm), and the tires were 700 mm in diameter and 23 mm in cross-sectional width
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33 (Vittoria Pro Team Kevlar®, Vittoria SA, Italy). They were inflated to a pressure of 9
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35 atmospheres. The cyclists only wore aero-helmets (Catlike crono®, Catlike SA, Spain)
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37 during the first three tests. The tests were static (without pedaling, position 1) and dynamic
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39 (pedaling against resistance, positions 2-5). The bicycle was fixed on a power meter (Elite
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41 Axiom Power Train ®, Italy) and both were placed on a force balance in order to measure
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43 the aerodynamic drag. The cyclists then warmed up for 15 minutes on the power meter in
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45 the wind tunnel (five minutes at $2 \text{ W}\cdot\text{kg}^{-1}$, five minutes at $3.5 \text{ W}\cdot\text{kg}^{-1}$ and five minutes at 5
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47 $\text{W}\cdot\text{kg}^{-1}$). After the warm-up, the cyclists pedaled for ten minutes at $5.5 \text{ W}\cdot\text{kg}^{-1}$, the same
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49 intensity being used for all the dynamic tests. This intensity corresponded to 90% of the
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51 $\text{VO}_{2\text{max}}$; the cyclists were able to maintain it for one hour, in theory (Atkinson *et al.*, 2003).
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3 During the five tests, aerodynamic drag measurements and cyclists' positions were
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5 simultaneously recorded with a force balance and two-dimensional photogrammetry.
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10 ****Figure 1 here****
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15 Aerodynamic drag measurements were obtained in a subsonic wind tunnel (up to $56 \text{ m}\cdot\text{s}^{-1}$).
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17 The tunnel was of the closed loop circuit type (Technological Institute of Renewable
18 Energy, ITER, Tenerife, Spain), with a testing section (2.2 m wide and 3 m long) to place
19 the bicycle and the cyclist, plus a control room to record all test variables (Figure 2)
20 (Gonzalez *et al.*, 1998). The wind speed (limited to $22 \text{ m}\cdot\text{s}^{-1}$ for safety reasons) was
21 controlled by a remote computer with a special software (ITER, Tenerife, Spain) and a
22 wind speed transducer (model TSI-8455®, USA, range 0.125 to $50 \text{ m}\cdot\text{s}^{-1}$ and precision of
23 $0.06 \text{ m}\cdot\text{s}^{-1}$). It sent the information through a micro controller connected to a system
24 (model Meltrac-A140E-220K®, Mitsubishi, USA) that changed the rotation frequency of
25 nine fans (model HCT-100-4T-30®, SODECA, England, power 22 kW and maximal
26 speed $1760 \text{ rev}\cdot\text{min}^{-1}$) in order to obtain the desired wind speed in the testing section (15
27 $\text{m}\cdot\text{s}^{-1}$ or $54 \text{ km}\cdot\text{h}^{-1}$). We selected a wind speed of $54 \text{ km}\cdot\text{h}^{-1}$ because cyclists aiming to
28 win individual time-trial races on flat terrain should average velocities higher than 50
29 $\text{km}\cdot\text{h}^{-1}$. Mean velocities in team time-trial races are even higher ($> 55 \text{ km}\cdot\text{h}^{-1}$).
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31 Nonetheless, Bassett *et al.* (1999) estimate that the cyclists' drag coefficient is typically
32 constant when wind speed ranges between 50 and $60 \text{ km}\cdot\text{h}^{-1}$.
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53 Before the tests, the force balance was zeroed at a wind speed of $15 \text{ m}\cdot\text{s}^{-1}$, to exclude the
54 aerodynamic drag of the power meter. Measurements were taken once the wind speed was
55 stabilized (around $15 \text{ m}\cdot\text{s}^{-1}$) in the force balance, which was a rectangular plate ($0.6\cdot 1.5 \text{ m}$
56 surface) equipped with a strain-gauge force transducer (model RS-632-742®, ranging from
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3 0 to 58.84 N and precision of 0.04 N). Force data were sampled at 10 Hz and
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6 synchronized with wind speed data. Both were captured by a special card
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8 (Daqboard/216^a®, Iotech Inc, USA, 16 bits and 100 kHz) and processed with Daqview®
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10 software (Iotech Inc., USA). The strain gauge was calibrated using calibration weights
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12 before the study and reset to zero before each trial. Measurements were registered at five
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14 intervals (2, 4, 6, 8, 10 min) for no longer than five seconds, taking the aerodynamic drag
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16 average as the reference value. Aerodynamic drag and wind speed were registered
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18 simultaneously; therefore the aerodynamic drag measurements were corrected for
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20 fluctuations of instantaneous wind speed (± 0.1 m/s).
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27 ****Figure 2 here****
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31 The variables derived from the aerodynamic drag (1) were obtained using Newton's
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33 equation (Hoerner, 1965). The drag area to body mass ratio ($SC_x \cdot kg^{-1}$) was calculated by
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35 dividing the drag area by the cyclist's body mass.
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$$41 \quad (1) \quad AD = 0.5 \cdot SC_x \cdot v^2 \cdot \rho$$

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43 where AD is the aerodynamic drag in N, S is the cyclist-bicycle frontal area in m^2 , C_x is
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45 the drag coefficient, SC_x is the drag area in m^2 , v is the wind speed, and ρ is the air density
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47 in $kg \cdot m^{-3}$.
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53 Assuming a negligible effect of air humidity (Grappe *et al.*, 1997; Di Prampero, 2000),
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55 we estimated the air density for each test with another formula (2) that takes ambient
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57 pressure and temperature into account (weather station, model BAR913H6®, Oregon
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59 Scientific Inc, USA).
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$$(2) \quad \rho = \rho_0 \cdot 0.359 \cdot P \cdot T^{-1}$$

where ρ is the air density in $\text{kg}\cdot\text{m}^{-3}$, ρ_0 is the standard air density ($1.293 \text{ kg}\cdot\text{m}^{-3}$) at 760 mmHg and 0°C (273 K), 0.359 is a constant relation (273 / 760) between standard pressure and standard temperature, P is the atmospheric pressure in mmHg, and T is the ambient temperature in K.

Cyclists' positions were analyzed by two-dimensional photogrammetry. One film of the cyclists' profile (sagittal plane) was taken every time the aerodynamic drag was measured. A model with seventeen anatomic markers on the cyclist's body was selected in order to reproduce his position on the bicycle, plus seven fixed markers for the bicycle (frame size, distance between the two shafts, etc.). All these markers were used to establish a scale and the relationship between the cyclist and the bicycle. We used a 25 Hz digital camera (GR-DVM75U®, JVC SA, USA) placed perpendicular to the sagittal plane. The representative image of the cyclist's position was selected with both cranks positioned horizontally. A special software was then used to analyze the images (Kinescan-2001®, IBV, Spain), allowing calculation of kinematic variables (Figure 3).

Figure 3 here

Before and after three tests (positions 3, 4 and 5) a frontal plane photograph was taken to calculate the cyclist-bicycle frontal area, taking the mean frontal area as the reference value. This was calculated by weighting (precision balance, model ER182A, A&D Company, Japan, precision $1\cdot 100000^{-1}$ g) and comparing the masses of the pictures of the cyclist-bicycle ensemble and that of the reference area (2.2 m reference system)

(Swain *et al.*, 1987; Olds and Olive, 1999). The cyclist's body surface area (3) was estimated using Du Bois and Du Bois' equation (Padilla *et al.*, 2000):

$$(3) \quad \text{BSA} = 0.007184 \cdot \text{BM}^{0.425} \cdot \text{H}^{0.725}$$

where BSA is the cyclist's body surface area in m^2 , BM is the cyclist's body mass in kg, and H is the cyclist's height in cm.

Graphic and Statistical Analysis

Data registry and graphical analysis were carried out using Microsoft Excel-v7.0 (Microsoft Inc, USA). Statistical analysis was carried out using Statistics-v4.5 for Windows (Statsoft Inc, USA). Results are expressed as the mean and standard error of the mean (SEM). Statistical differences between the five tests were analyzed by repeated ANOVA measures. Relationships between variables were analyzed by non-parametric Spearman test. Differences and correlations were considered significant when $P < 0.05$.

Results

Table 1 shows that the drag area increased significantly (by 31%) in position 2 (during effort) with respect to position 1 (static). It later decreased (by 14%) in position 3 (modifications to the handlebars) with respect to position 2, and did not change in position 4 (without aero-helmet) with respect to position 3. Drag area values in positions 1 to 4 (time-trial bicycle) were significantly lower ($P < 0.05$) than in position 5 (standard racing bicycle). Frontal area and drag coefficient were significantly higher

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3 (P<0.05) in position 5 than in positions 3 and 4. Horizontal-torso angle was the only
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5 kinematic variable related to drag area (Table 2). We found significant correlations
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7 (P<0.05) between this variable, drag area (r=0.42, Figure 4), and drag area to body mass
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9 ratio (r=0.40).
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15 ****Table 1 here****
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24 Table 2 summarizes significant correlations when the time-trial bicycle was used. Apart
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26 from the correlations between anthropometric variables, the correlations between drag
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28 area to body mass ratio and other variables were notable. The relation between drag area
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30 and drag area to body mass ratio was significant (r=0.69, P < 0.001).
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36 ****Table 2 here****
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41 Table 3 shows that all cyclists obtained the lowest drag area in positions 3 and 4. The
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43 use of an aero-helmet (position 3) reduced drag area in three cyclists (subjects 2-4),
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45 raised it in subject 1, and had no effect in subject 5.
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51 ****Table 3 here****
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55 In the five cyclists studied, the minimum drag area did not coincide with the minimum
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57 drag area to body mass ratio (Figure 5).
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3 ****Figure 5 here****
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8 In each of the five tests, the five drag area measurements showed high reliability (Table
9 4) and the mean coefficient of variation (CV) for all measurements was 1.1% (0.3-2.0%
10 range).
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17 ****Table 4 here****
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24 Discussion

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29 In this study we obtained reference values of aerodynamic drag in a representative group
30 of professional cyclists who used different positions on the bicycle. We compared our
31 cyclists' values with those obtained by other authors and observed a high variability of
32 drag area values for the same position (Grappe *et al.*, 1997; García-López *et al.*, 2002):
33 upright position between 0.299-0.390 m², dropped position between 0.251-0.370 m²,
34 aerodynamic position between 0.191-0.304 m², and optimized positions (e.g. Obree's
35 and Boardman's positions) between 0.172-0.275 m². This could be due to a number of
36 methodological problems that we refer to in the following paragraphs.
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48 a) Varying techniques have been used to measure the aerodynamic drag, some of which
49 may not be sufficiently valid or reliable to estimate the drag area. These techniques are: 1)
50 the traction resistance test, because the towing vehicle and the atmospheric conditions
51 alter the measurements (De Groot *et al.*, 1995). 2) The lab-to-field extrapolation of
52 mechanical power and metabolic rate also has drawbacks, such as different
53 environmental and/or physiological conditions between laboratory and field
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3 measurements (Brooks *et al.*, 2000). 3) The simplified deceleration method overestimates
4 the aerodynamic drag (3.8%) and its test-retest reliability is low (CV<10%) (Hoerner,
5 1965). Candau *et al.* (1999) showed that high reliability is possible (CV 1-2%),
6 although the large number of trials and the cyclist's difficulty to repeat the same
7 position can be a problem. 4) Force transducers on the rear-wheel hub or on the crank
8 (SRM®, Max One® and Power-Tap®) are useful to measure power output during
9 training, competitions and laboratory testing (Bertucci *et al.*, 2005a), but their validity,
10 reliability (Gardner *et al.*, 2004), and sensitivity to measure the aerodynamic drag has
11 yet to be demonstrated.
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25 b) It is very difficult to reproduce a position on the bicycle and to obtain exactly the same
26 aerodynamic drag values. Kyle (1979) measured the drag coefficient in the same position
27 as it was measured previously by Kawamura (1953) (both were wind-tunnel studies) (cited
28 in Grappe, F. *et al.*, 1997, Aerodynamic drag in field cycling with special reference to the
29 Obree's position. *Ergonomics*, 40, 1299-1311), found variations of around 5%, and
30 concluded that this depended on the geometrical figure (filmed in the sagittal plane), which
31 is notably difficult to standardize.
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41 c) The mathematical models consider that the cyclist's frontal area is proportional to his
42 body surface area (between 15-20%) (Faria *et al.*, 2005). A drag coefficient is then
43 assigned to that profile and the drag area is obtained, although this only provides an
44 estimate instead of the real value. Swain *et al.* (1987) demonstrated that the frontal area is
45 not a fixed proportion of body surface area, because the body surface area to body mass
46 ratio is lower in heavier cyclists. We observed that the drag area values obtained in wind-
47 tunnel were not related to the body surface area (Table 2). This is why there is much
48 controversy about the power needed to break the one-hour cycling world record. While the
49 calculated average power (wind-tunnel data) was 510 W for Indurain's record (Padilla *et*
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3 *al.*, 2000), other authors, using a mathematics model, calculated an average power of
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5 around 436 W (Basset *et al.*, 1999).
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8 d) The cycling equipment used during the tests varied from one study to the other. Dal
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10 Monte *et al.* (1987) obtained values in a range of 0.246-0.280 m² in 11 wind tunnel tests
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12 repeated by the same cyclist but with varying equipment (e.g. frame, wheels, clothes,
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14 and helmet). They used a regular frame, which increases the drag area by 0.020 m²
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16 when compared to an aerodynamic frame (Jeukendrup and Martin, 2001). They also
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18 used disk wheels, which were shown to reduce the drag area by between 0.013 m²
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20 (Greenwell *et al.*, 1995) and 0.040 m² (Tew and Sayers, 1999) when measured against
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22 conventional wheels. According to Kyle *et al.* (1986), few clothing (helmet included)
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24 can reduce the aerodynamic drag with respect to well-shaved bare skin, although the
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26 same authors add that covering both cycling shoes with spandex can reduce the drag
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28 area by 0.003 m². Only one study (Menard, 1992) reported its time-trial bicycle (cycle
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30 only, no cyclist) drag area (0.146 m², with an aerodynamic frame, an aero-handlebar
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32 and two conventional wheels). Our time-trial bicycle presented a slightly lower drag
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34 area (0.122 m²) with analogous equipment (aerodynamic frame, aero-handlebar and two
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36 conventional wheels). The use of handlebars and helmets will be discussed later.
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46 In the present study, the best position on the time-trial bicycle for each cyclist yielded
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48 drag area values ranging between 0.255-0.299 m² (Table 3). In another wind-tunnel
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50 study, Bassett *et al.* (1999) found drag area values much lower than ours (0.187-0.230
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52 m²) for cyclists with comparable anthropometrical characteristics (Table 5). We
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54 observed that most wind-tunnel studies, including the one by Bassett *et al.* (1999),
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56 evaluated the drag area in static positions (Dal Monte *et al.*, 1987; Menard, 1992;
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58 Padilla *et al.*, 2000; Jeukendrup et Martin, 2001), while we found that static values
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3 (Table 1, Position 1) were lower than dynamic values (Table 1, Positions 2-4) by 31%.
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5 This seems to be the main explanation as to why our results are higher than the ones
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7 reported by other authors.
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10 To our knowledge, only one other wind-tunnel study evaluated the drag area during effort
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12 on a time-trial bicycle (Martin *et al.*, 1998). The drag area values it measured (0.269 ± 0.004
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14 m^2) are slightly lower than ours (by 0.024 m^2) for comparable cyclists ($1.77 \pm 0.05 \text{ m}$ and
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16 $71.9 \pm 6.3 \text{ kg}$). This could be explained by the following methodological divergences: a)
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18 our bicycle was equipped with two conventional oval spokes wheels, while Martin *et al.*
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20 (1998) used a rear disk wheel and a front conventional oval spokes wheel. Since it was
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22 shown that the use of a front disk wheel reduces the drag area by about 0.027 m^2
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24 (average of the values of Greenwell *et al.*, 1995 and Tew and Sayers, 1999), and that it
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26 is estimated that the rear wheel causes 50% less resistance than the front wheel
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28 (Jeukendrup and Martin, 2001), this should account for only 0.013 m^2 of the total
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30 difference. b) Our cyclists pedaled at race pace ($5.5 \text{ W} \cdot \text{kg}^{-1}$), while those in the study by
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32 Martin *et al.* (1998) simulated pedaling against no resistance. This might account for the
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34 remaining difference (0.014 m^2), since we cannot compare the drag area of the time-trial
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36 bicycle we used (0.122 m^2) with theirs. c) The front wheel did not rotate in our study,
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38 because it was fixed on an Axiom ergometer. This could slightly affect the aerodynamic
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40 drag measurement. However, careful examination of the data of Tew and Sayers (1999)
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42 reveals that there was no significant difference of aerodynamic drag when 36 oval
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44 spokes wheels rotated at varying speeds (with a yaw angle of 0°), which leads us to
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46 believe that the front wheel's rotation impact, if there is any, should be minimal. Futures
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48 studies should evaluate the exact impact of the rotation of the front wheel on the drag
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50 area.
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****Table 5 here****

Drag area should be expressed in absolute terms (e.g. 0.255 m^2), but also in relative terms (drag area to body mass ratio, e.g. $3.5 \cdot 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$), because both variables provide a different appreciation of the cyclists' aerodynamics. We calculated these two variables in ours and Bassett *et al.* (1999) cyclists' (Table 5 and Figure 6), and found that small cyclists had a higher drag area to body mass ratio than large ones (and therefore worse aerodynamics). Swain (1994) also observed this trend, and added that this is not compensated by a higher relative $\text{VO}_{2\text{max}}$ in small cyclists. This explanation can be related to the "allometric scale" concept (Astrand and Rodahl, 1986), which implies a lower mass exponent for drag area (1/3) than $\text{VO}_{2\text{max}}$ (2/3) (Faria *et al.*, 2005). Lucia *et al.* (2000) also noted significant differences of body mass (12.4%) between climbers ($64.3 \pm 2.2 \text{ kg}$) and time trialists ($72.3 \pm 2.3 \text{ kg}$), but not of relative power output at $\text{VO}_{2\text{max}}$. After having applied the equations of Figure 6 to the cyclists of Lucia *et al.* (2000), we found that the drag area to body mass ratio was 9.8-17.4% higher for climbers. This is a disadvantage for small cyclists, for the reasons explained previously. The two following anecdotal examples relate to that notion: subject 3 of the present study (61 kg) lost the *Vuelta a España* 2001 by 62 s in the last stage (individual time-trial, 38 km on level ground) to a much larger cyclist (74 kg). Conversely, subject 4 (69 kg) won the *Vuelta a España* 2002 by 132 s in the last stage (individual time-trial, 41.2 km on level ground) because he was able to beat a smaller cyclist (60 kg).

****Figure 6 here****

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3 The frontal areas (Table 1) we obtained on time-trial bicycle ($<0.31 \text{ m}^2$) by a direct method
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5 (Swain *et al.*, 1987) were lower than those estimated by indirect methods such as body
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7 surface area ($>0.40 \text{ m}^2$) in cyclists with similar anthropometric characteristics (Capelli *et*
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9 *al.*, 1998; Di Prampero, 2000). We did not find any correlation between body surface area
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11 and frontal area measured by a direct method (Table 2). Heil (2001) found a low
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13 correlation between these two variables, because frontal area also depended on the
14
15 horizontal-torso and seat-tube angles. The frontal areas were a little higher ($0.318\text{-}0.322$
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17 m^2) than in our study ($0.301\text{-}0.305 \text{ m}^2$), although the horizontal-torso angles were similar
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19 (around 15°). This was because the cyclists studied by Heil (2001) were a little larger (74.4
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21 kg and 1.82 m). Drag coefficients we obtained (Table 1) were higher than those obtained
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23 by other authors on time-trial ($0.55\text{-}0.75$) and standard racing ($0.8\text{-}1.0$) bicycles (Capelli *et*
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25 *al.*, 1998; Di Prampero, 2000; Padilla *et al.*, 2000). Several factors can explain this
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27 difference: carrying out the test during effort, obtaining the frontal area by a direct method,
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29 and using the wind tunnel and not other techniques.
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36 We compared the modifications in drag area we obtained to those of other studies even if
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38 the methodology varied from one study to the other. In our study, the International Cycling
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40 Union rules (UCI, 2006) were taken into account. Modifications to the handlebar position
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42 (forearm support) decreased the drag area by 14% (Table 1). Similar results were obtained
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44 by other authors when comparing different positions on the bicycle (upright, dropped,
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46 aerodynamic and optimized positions) (Grappe *et al.*, 1997). The individual modifications
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48 decreased the horizontal-torso angle (Table 1, Positions 2-4), and this was associated with
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50 a lower drag area. Jeukendrup and Martin (2001) obtained similar decreases of drag area
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52 (11%) when the aerodynamic handlebar was modified, but their study focused on only one
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54 cyclist. Heil *et al.* (1997) described the metabolic cost increases and kinematic variations
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56 of hip, knee and ankle angles when cyclists used horizontal-torso angles in a range of 10-
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3 20° (similar to our study). Nevertheless, Grappe *et al.* (1998) reported that, at high speed
4 (from 11 m·s⁻¹), the metabolic cost increases would be compensated by a reduction of
5 aerodynamic drag, resulting in performance improvement. The limitation of our study
6 and that of Jeukendrup and Martin (2001) was that the metabolic cost impact of modifying
7 the cyclists' position was not evaluated. While these new positions improved the
8 aerodynamic drag, they might have increased the metabolic cost required to produce
9 cycling power. Also, past studies examined physiological and biomechanical responses
10 when cyclists used aerodynamic handlebars and positions, but did not study the cyclists'
11 adaptation to these positions. That is, it is possible that the increase in metabolic cost
12 associated with an unusual position be reduced by training in that specific position;
13 future studies should evaluate whether the potential increase in metabolic cost induced by a
14 new position is counterbalanced by training in that position.

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32 In our study, the use of an aero-helmet did not decrease the drag area for all cyclists
33 (Table 1). After biomechanical evaluation, we produced a report for each cyclist with
34 recommendations regarding the best position to adopt and whether to use or not the aero-
35 helmet, since cyclists were allowed to compete with or without helmet until 2003. Some
36 authors reported that wearing a rubber helmet decreased the drag area (by 0.4%),
37 however, their results were obtained using a scaled wind tunnel (0.61·0.81 m testing
38 section) and a mannequin head (Kyle and Caiozzo, 1986; Kyle, 1989). Dal Monte *et al.*
39 (1987) measured in a wind tunnel the impact of four types of aero-helmet on the drag
40 area of one cyclist. Only one type decreased the drag area, but it was too uncomfortable
41 and the cyclist refused to use it. These authors suggested that the helmet geometry must
42 be adapted to each cyclist in order to decrease the drag area. Nowadays it is impossible
43 to compete without a safety headgear, due to the new competition rules (UCI, 2006,
44 article 1.3.031). However, there is still no study to prove the aerodynamic efficiency of
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3 this safety headgear, especially in individual and team time-trial races. Future studies
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5 should examine this aspect.
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8 It would be much simpler and practical to carry out aerodynamic drag testing in field
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10 conditions, without the use of a wind tunnel. Several investigations aimed to do so in a
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12 variety of facilities (i.e. a 80-m-long level indoor hallway, a taxiway airport, and a
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14 velodrome) (Candau *et al.*, 1999; Martin *et al.*, 2006). The main limitations of these
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16 studies are: a) controlling and replicating the atmospheric conditions, b) building a sport
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18 specific facility, and c) taking into account that the air resistance is lower when riding
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20 around a velodrome curve than when cycling in strait line (Olds, 2001). Future research
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22 should attempt to model and compare field data collected in velodrome with wind-
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24 tunnel data. Hence, we think that the wind tunnel is still nowadays the reference method
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26 to measure the aerodynamic drag in cycling, because: a) it is very sensitive to small
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28 changes in aerodynamic drag, whereas no study of the SRM powermeter demonstrated
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30 such sensitivity. b) It is very reliable. We found a high test-retest reliability ($r > 0.96$ and
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32 $P < 0.001$, Table 4) and a low coefficient of variation ($< 2\%$). This coefficient was lower
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34 than the significant differences in this study. Still, no study of the SRM powermeter
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36 assessed its test-retest reliability in measuring derived parameters of aerodynamic drag
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38 (e.g. drag area).
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45 In addition, future wind-tunnel studies should take into account the following
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47 methodological considerations, which were not addressed in the present study: a) the
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49 pedaling “at race pace” should be lower than $5.5 \text{ W} \cdot \text{kg}^{-1}$. We chose $5.5 \text{ W} \cdot \text{kg}^{-1}$ based on
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51 theoretical estimates of previous studies (Atkinson *et al.*, 2003), and the cyclists
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53 maintained it without difficulty during 10 minutes. However, Vogt *et al.* (2006) recently
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55 measured an average power output of $5.5 \text{ W} \cdot \text{kg}^{-1}$ during a 13 km uphill time trial which
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3 lasted 23 minutes. The pedaling intensity should be lowered so that it represents more
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5 adequately the average power maintained for 30-60 minutes.
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8 b) The bicycle should be fixed on a valid power meter. We used the Elite Axiom Power
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10 Train, and Bertucci *et al.* (2005b) recently showed that it does not provide a valid power
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12 output measurement. The power output was probably closer to $4.9\text{-}5.0\text{ W}\cdot\text{kg}^{-1}$.
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14 Moreover, the power meter should allow lateral movement of the cyclist-bicycle
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16 system, since these affect the estimation of the power output in the laboratory (Bertucci
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18 *et al.*, 2005c) and could affect the aerodynamic drag measurements.
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20 c) The aerodynamic drag measurements should be done during longer and homogenous
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22 time intervals ($\sim 30\text{ s}$). Only Martin *et al.* (1998) (30 s) and the present study (5 s)
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24 specified these time intervals; it would be interesting to implement a standard interval
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26 time in wind-tunnel cycling studies. Thirty seconds seems most appropriate, since
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28 longer measurement intervals would improve the data's reliability.
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31 d) The force balance and the bicycle's crank should be synchronized. Our wind tunnel,
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33 like most tunnels not designed with a sporting application, did not offer this possibility.
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35 None of the published wind-tunnel studies synchronized the force balance and the
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37 bicycle's cranks. It is important to do so, so that the aerodynamic drag may be exactly
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39 registered based on the number of complete turn of the crank, avoiding possible
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41 interferences of the forces applied to the pedals.
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48 e) The front wheel should rotate, for the reasons we explained previously.
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52 **Conclusions**

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57 We have obtained reference values of aerodynamic drag in five professional cyclists in
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59 a wind tunnel, and found a high level of heterogeneity in the drag area values presented
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3 by other authors with respect to the same bicycle positions; this was due to a number of
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5 methodological considerations that should be considered in the future. Drag area values
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7 were higher than those obtained by other wind-tunnel studies that did not assess the
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9 aerodynamic drag during effort at race pace and that used different wheels. Bicycle
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11 modifications decreased cyclists' aerodynamic drag by 14%, although future studies
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13 should evaluate the training and metabolic adaptations induced by these modifications.
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15 The use of the aero-helmet did not decrease the aerodynamic drag in all cyclists,
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17 because the helmets were not individualized. Future studies should investigate the
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19 aerodynamic efficiency of new safety headgear. The drag area to body mass ratio could
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21 be a good indicator of aerodynamic performance and it tends to be higher in small
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23 cyclists. Future studies should take this into account. Similar studies under field
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25 conditions (i.e. in indoor cycle tracks) are necessary. For this purpose, it is necessary to:
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27 1) asses the reliability and sensitivity in measuring the drag area of the mobile
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29 ergometers available, and 2) validate a mathematical model to measure drag area during
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31 steady-state cycling in velodrome, where the atmospheric conditions can be easily
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33 reproduced. At this time, the wind tunnel is the reference method to measure drag area in
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35 cycling, because it has demonstrated high reliability and sensitivity. Nevertheless, future
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37 studies should take into in account the methodological considerations mentioned
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39 previously in order to increase its validity.
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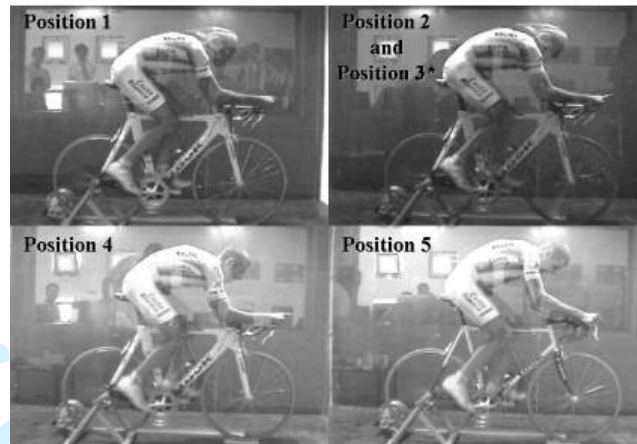
Figures

Figure 1. The five positions analyzed in this study. On the time-trial bicycle: position 1- static, with the original configuration used by the cyclists and both cranks placed horizontally; position 2- dynamic, similar to 1, but during effort at race pace ($5.5 \text{ W}\cdot\text{kg}^{-1}$) for ten minutes; position 3*- similar to 2, but after lowering the handlebars and advancing the pads (forearm support) by 2-3 cm; position 4- similar to 3, but without aero-helmet. On the standard racing bicycle: position 5- grabbing handlebars and without helmet. * It was impossible to represent the picture differences with respect to position 2.

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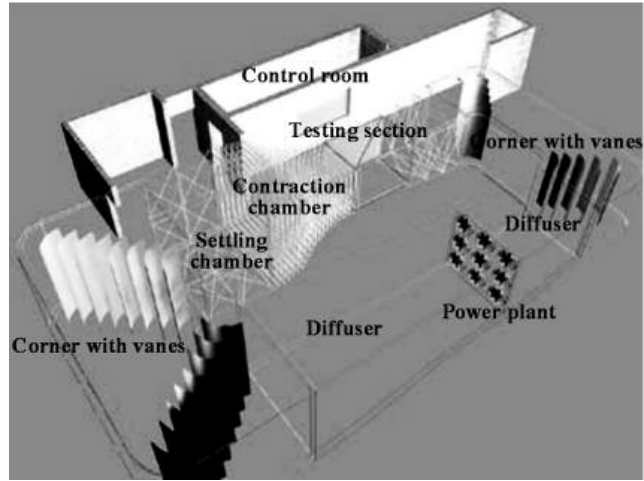


Figure 2. Characteristics of the closed loop circuit subsonic wind tunnel (Technological Institute of Renewable Energy, ITER, Tenerife, Spain).

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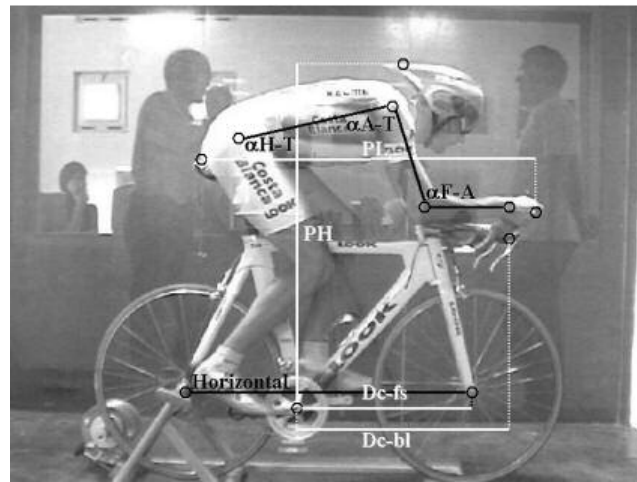


Figure 3. Kinematic variables of the cyclist and bicycle. PH: profile height, PL: profile length, Dc-fs: horizontal distance between the crank and the front shaft, Dc-bl: horizontal distance between the crank and the brake levers. Angles: α_{H-T} (horizontal-torso), α_{A-T} (arm-torso) and α_{F-A} (forearm-arm).

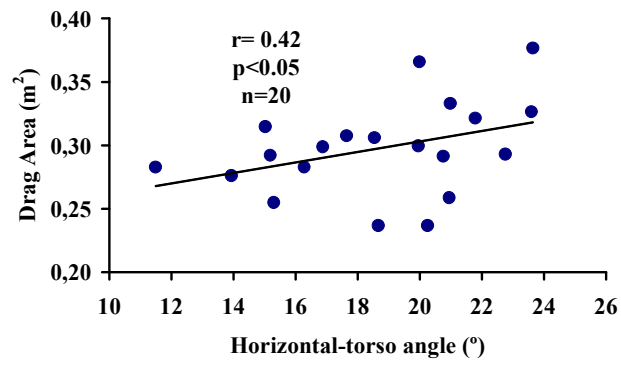


Figure 4. Correlation between drag area and horizontal-torso angle on the time-trial bicycle. Significant correlation ($P<0.05$).

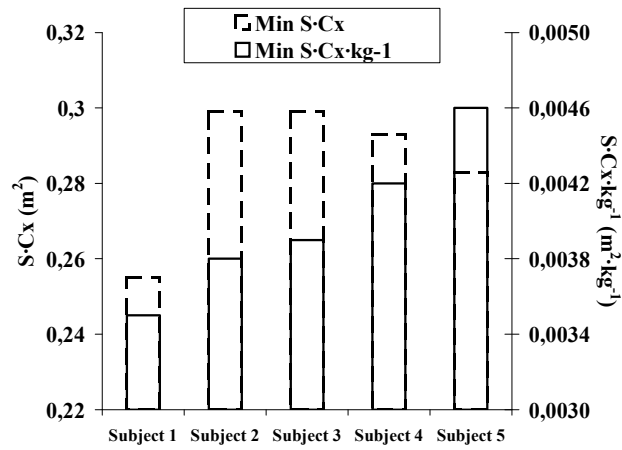


Figure 5. The minimum drag area ($Min S \cdot C_x$, solid line) and the minimum drag area to body mass ratio ($Min S \cdot C_x \cdot kg^{-1}$, dotted line) in the five cyclists.

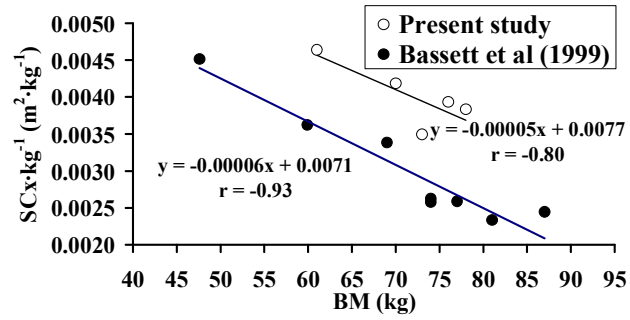


Figure 6. Correlation between drag area to body mass ratio ($SCx \cdot kg^{-1}$) and body mass (BM) on time-trial bicycle. Present study (the best position for each cyclist, $n=5$) and Broker *et al.*, 1999 (compilation of two studies, $n=8$).

Tables

Table 1. Aerodynamic drag measurements and kinematic variables in the five positions (mean + SEM).

	Position 1	Position 2	Position 3	Position 4	Position 5
SCx (m²)	0.260±0.011	0.341±0.013*	0.293±0.003*	0.297±0.013	0.481±0.017*
S (m²)	-	-	0.305±0.008	0.301±0.011	0.364±0.012*
Cx	-	-	0.96±0.03	0.99±0.05	1.33±0.07*
αH-T (°)	16.9±1.2	19.2±1.2*	15.4±1.5*	15.8±1.4	23.1±2.2*
αA-T (°)	86.6±4.1	84.0±3.9	86.1±2.2	84.1±1.6	76.8±2.1*
αF-A (°)	106.8±3.9	109.6±4.1	107.8±2.9	108.8±4.0	119.8±7.7*
PH (cm)	114.5±2.1	121.4±2.0*	116.1±2.6*	112.8±2.6	114.6±2.9*
PL (cm)	89.4±3.4	85.4±2.1*	87.3±1.7*	85.5±1.8*	85.7±1.9
Dc-fs (cm) †	57.5±0.9	57.7±0.9	57.7±0.8	57.8±0.8	58.7±0.7*
Dc-bl (cm) ‡	71.2±2.3	71.3±1.8	73.0±2.3*	73.2±2.0	68.9±2.1*

SCx: drag area. S: frontal area. Cx: drag coefficient. See Figure 3 for the definition of other terms. * Significantly different from previous position (P<0.05). International Cycling Union rules: † maximum distance of 65 cm (article 1.3.016), ‡ maximum distance of 75 cm (article 1.3.023).

Table 2. Correlations between anthropometric, kinematic, and drag area variables, on time-trial bicycle.

	BM (kg)	H (m)	BSA (m²)	αH-T (°)	S·Cx (m²)
H (m)	0.90***				
BSA (m²)	0.92***	0.90***			
αH-T (°)	-	-	-		
SCx (m²)	-	-	-	0.42*	
SCx·kg⁻¹ (m²·kg⁻¹)	-0.54***	-0.42*	-0.54***	0.40*	0.69***

H: Cyclist's height, BM: Cyclist's body mass, BSA: Body surface area, αH-T: Horizontal-torso angle, SCx: drag area, SCx·kg⁻¹: drag area to body mass ratio. Significant correlations: * = P<0.05; ** = P<0.01; *** = P<0.001.

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Table 3. Drag area for each subject in the five positions, minimum drag area to body mass ratio and aero-helmet influence.

	Position1 SCx (m ²)	Position2 SCx (m ²)	Position3 SCx (m ²)	Position4 SCx (m ²)	Position5 SCx (m ²)	Min SCx·kg ⁻¹ (m ² ·kg ⁻¹)	Helmet Inf. (%)
Subject 1	0.237	0.366	0.292	0.255	0.469	3.5·10 ⁻³	+14.5
Subject 2	0.276	0.307	0.299	0.315	0.521	3.8·10 ⁻³	-5.1
Subject 3	0.291	0.321	0.299	0.306	0.515	3.9·10 ⁻³	-2.3
Subject 4	0.237	0.377	0.293	0.326	0.469	4.2·10 ⁻³	-10.1
Subject 5	0.259	0.333	0.283	0.283	0.428	4.6·10 ⁻³	0.0
Mean	0.260	0.341	0.293	0.297	0.481	4.0·10 ⁻³	-1.3
SEM	0.010	0.012	0.003	0.011	0.015	0.2·10 ⁻³	0.08

SCx: Drag area in each position. Min SCx·kg⁻¹: Minimum drag area to body mass ratio from effort positions. Helmet Inf.: aero-helmet influence. In bold type, the minimum drag area values for each cyclist.

Table 4. Correlations of the five drag area measurements carried out during the five test for the five cyclists (n=125).

	Interval 1	Interval 2	Interval 3	Interval 4
Interval 2	0,98			
Interval 3	0,98	0,99		
Interval 4	0,96	0,98	0,99	
Interval 5	0,96	0,97	0,98	0,99

Significant correlations (P<0.001).

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Table 5. Drag area for eight subjects in a wind tunnel on time-trial bicycle (reported by Bassett *et al.*, 1999).

	H (m)	BM (kg)	AD (N)	SCx (m²)	SCx·kg⁻¹ (m²·kg⁻¹)
Subject 1^a	1.63	47.6	23.00	0.212	4.5·10 ⁻³
Subject 2^a	1.75	59.9	23.22	0.214	3.6·10 ⁻³
Subject 3^a	1.80	69.0	24.99	0.230	3.3·10 ⁻³
Subject 4^b	1.80	74.0	21.01	0.194	2.6·10 ⁻³
Subject 5^b	1.80	74.0	20.42	0.188	2.5·10 ⁻³
Subject 6^b	1.80	77.0	21.35	0.197	2.6·10 ⁻³
Subject 7^b	1.86	81.0	20.24	0.187	2.3·10 ⁻³
Subject 8^b	1.93	87.0	22.79	0.210	2.4·10 ⁻³
Mean	1.80	71.2	22.13	0.207	3.0·10 ⁻³
SEM	0.03	4.1	0.54	0.005	0.2·10 ⁻³

H: Cyclist's height, BM: Cyclist's body mass, AD: Aerodynamic drag, SCx: drag area, SCx·kg⁻¹: drag area to body mass ratio. ^aKyle's and ^bBroker and Kyle's original data: Wind speed of 48 km·h⁻¹, assuming that air density was 1.204 kg·m⁻³ (at sea level and 20 °C, equation 2).