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Aerodynamic drag in field cycling with special reference to the Obree's position

FREDERIC GRAPPE, ROBIN CANDAU, ALAIN BELLI† and JEAN DENIS ROUILLON

Laboratoire des Sciences du Sport, UFR-STAPS de Besançon, 2 Place Saint Jacques, 25030 Besançon cedex, France

†Laboratoire de Physiologie–GIP Exercice, Faculté de Médecine de Lyon-Sud, Oullins, France

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In cycling at race speeds, 90% of total resistance opposing motion, R_T(N) depends on aerodynamic drag of air, which is directly proportional to the effective frontal area, AC_d(m^2). R_T was measured on a cyclist, in an open velodrome, in order to evaluate AC_d in four different positions on a traditional bicycle : upright position (UP), dropped position (DP), aero position (AP) and Obree's position (OP : the hands in support under the chest, the forearms tucked on the arms, the trunk tilted forward). R_T was determined at different constant speeds, Vc(m s^{-1}) with a special device (Max One), which allows the measurement of the external mechanical power P_{ext}(W) in real conditions of cycling locomotion ($R_T = P_{ext} Vc^{-1}$). Experiments were carried out in order to test the validity and the reproducibility of P_{ext} provided by the measurement device. P_{ext} was measured twice in the same experimental conditions (exercise on a treadmill against slopes varying from 1 to 14%) and no significant difference was observed between the two measurement series. A systematic measurement error was observed allowing the use of a correcting factor. As expected, in the four rider positions, R_T increased linearly ($p < 0.001$, $r = 0.90–0.95$) with Vc^2. AC_d were significantly different ($p < 0.001$) between the four positions, except between DP and AP. As compared to UP, in DP, AP and OP the significant reductions of AC_d were 7.8, 12.4 and 27.8%, respectively. These reductions were associated with the degree of rachis flexion and with the decrease of the lateral distance between the two upper limbs. In UP, AC_d (0.299 m^2) was lower (−23%) than those reported in previous studies. In DP and AP, AC_d (0.276 m^2 and 0.262 m^2, respectively) were similar to those reported in previous studies. In OP, no study allowed a real comparison with the value of AC_d (0.216 m^2) found in this study. The average rolling resistance ($Rr = 1.95 \pm 0.81$ N) determined according to the four positions was in line with previous reports. These findings suggest that the position adopted by Obree significantly reduces the aerodynamic drag and, thus, is an important factor in cycling performance.

1. Introduction

The total resistance opposing the motion of a cyclist, R_T(N) [see appendix for list of abbreviations] on a flat terrain can be described by equation 1 (Capelli *et al.* 1993, Davies 1980, Di Prampero *et al.* 1979, Ménard 1992, Ménard *et al.* 1990, Pugh 1974, Whitt 1971):

$$R_T = 0{\cdot}5 \rho AC_d Va^2 + C_r m\,\mathbf{g} \quad (1)$$

where the first term represents the aerodynamic drag of air, Ra(N) and the second term the rolling resistance, Rr(N). Ra increases as (1) the square of the air speed Va(m s^{-1}) opposing the motion of the bicycle-rider combination (BRC), (2) the aerodynamic drag coefficient of BRC (C_d), (3) the projected frontal area of BRC, A(m^2), and (4) the air density, ρ(kg m^{-3}). Ra is almost directly proportional to the product of A and C_d and for convenience (it is difficult to quantify the term A with precision in cycling), the two variables can be associated (Gross *et al.* 1983, Ménard 1992) to determine the effective frontal area, AC_d(m^2) of the BRC. According to Kyle *et al.* (1973) and Kyle and Burke (1984), Rr can be described by the following equation: $R\text{r} = a_0 + a_1 V\text{c}$ (where Vc is cyclist speed in m s^{-1}). The second term $a_1 V$c is neglected as being insignificant in Rr. Thus, in numerous studies Rr was considered constant with Vc and proportional to the rolling coefficient (C_r) and the force, $m\,g$(N) (where m = mass of subject + bicycle (kg); g = 9.81 m s^{-2}) applied on the bicycle tyres and perpendicular to the rolling surface (Capelli *et al.* 1993, Davies 1980, Di Prampero *et al.* 1979, Ménard 1992, Ménard *et al.* 1990, Pugh 1974, Whitt 1971). Ra reaches 90% of R_T at typical race speeds (13 m s^{-1}) while Rr represents a lower proportion of R_T (Di Prampero 1986, Di Prampero *et al.* 1979, Gross *et al.* 1983, Kyle and Edelman 1975). Seventy percent of R_T is due to Ra of the rider and 30% to Ra of the bicycle (Gross *et al.* 1983). In calm air, the mechanical power used to overcome Ra increases as $V\text{c}^3$. Cyclists need to redouble their power to increase their speed from 9 m s^{-1} to only 12 m s^{-1} (Gross *et al.* 1983). Human power output is limited and it is necessary to minimize AC_d to reach high Vc and to maintain it during long periods. Therefore, in order to improve cycling performance, the cyclist must mainly improve his aerodynamics with an adequate position on the bicycle.

Three main positions are generally used by cyclists according to the type of race and to the profile of the terrain. Upright posture (UP), characterized by the hands on the upper part of the handlebars, is mainly used when pulling up on the handlebars to ride in hill terrain. Dropped posture (DP), the hands on the bottom of the handlebars, is adopted at high Vc, to minimize AC_d. Aero posture (AP), when the elbows are placed on the pads of the aero-handlebars, is the best aerodynamic position to overcome Ra. It is mainly used during time-trials. AC_d in DP has been measured by numerous authors (Pugh 1974, Kyle and Edelman 1975, Di Prampero *et al.* 1979, Davies 1980, Gross *et al.* 1983, Kyle and Burke 1984, Ménard 1992, Ménard *et al.* 1990, Capelli *et al.* 1993, Kyle *et al.* 1973). Indeed, for a long time DP was the best aerodynamic posture for a cyclist. UP was considered as a touring position and was the subject of fewer investigations (Kyle and Edelman 1975, Gross *et al.* 1983). AC_d values in AP have been compared to DP (Kyle 1989) and were recently reported by Ménard *et al.* (1990) and Ménard (1992). In July 1993, Obree adopted a new position (OP) in track and established a new distance record (52.713 km) during 1 h of cycling. The hands were in support under the chest, the forearms tucked on the arms, the trunk tilted forward close to the horizontal plane. To the best of our knowledge, AC_d values in OP have not yet been reported and compared in the literature. This may be explained by the fact that OP is a new position. Thus, the benefit that would be expected in OP as compared with the three other positions is not well established.

In UP, DP, AP and OP the changes in trunk flexions and upper limb positions determine changes in AC_d. Thus, the purpose of the present study was to compare in an elite cyclist AC_d in UP, DP and AP with special reference to OP. Contrary to the other methods (Kawamura 1953, Kyle and Burke 1984, Ménard *et al.* 1990, Nonweiler 1956, Davies 1980, Pugh 1974, Di Prampero *et al.* 1979, Capelli *et al.* 1993, Kyle and Edelman 1975) the measurement of AC_d was performed in the field, in a real situation of cycling locomotion, in order to take into account the cyclist's natural gestures that occur during the exercise. For that purpose a specific measurement device allowing measurements in field conditions was used and calibrated beforehand by a test procedure.

2. Methods

2.1. *Subjects*

Twelve national and regional competitor cyclists (mean $\pm$SD: age = 20.2 ± 1.3 years; height = 1.77 ± 0.045 m; weight = 72.5 ± 3.2 kg) participated in this investigation. These subjects were previously permitted, by a test procedure, to calibrate the specific measurement device used in this study. They were selected for their skill to ride on a treadmill with their road bicycle. The AC_d determination in the different positions was conducted on one of the twelve subjects (a national elite cyclist, weight = 67 kg and height = 1.75 m). The anthropometric characteristics of this subject (important to estimate the subject's form) were determined using the Health and Carter somatotype rating form (Health and Carter 1967). The three components (endomorphy, mesomorphy, and ectomorphy) calculated for the subject were 1.5, 6, and 3, respectively.

2.2. *Determination of* AC_d

The rider exercised with his personal road bicycle on an open velodrome 453.89 m long (Besançon, France, 246 m above sea level). The velodrome track was covered with a synthetic resin surface. The test was performed in calm air: barometric pressure (P_B) = 756 mmHg, temperature (T) = 12°C, wind speed, Vw (m s^{-1}) was measured by means of an anemometer (Jules Richard, Argenteuil, France, accuracy = $\pm$2%) and varied from 0.5 to 1 m s^{-1}. Four sets of measurements were performed in UP, DP, AP and OP. In all the sets the bicycle was the same traditionally framed cycle with spoke wheels. The tyres were inflated at 7 bars. AC_d was determined according to equation 1 with R_T measurements in the four different experimental conditions. For each position, the cyclist performed a discontinuous incremental exercise of twelve laps at different Vc performing a total of 48 laps (i.e. 4×12 laps). Vc was set at 5.5 m s^{-1} for the initial lap and was incremented by 0.5 m s^{-1} between each consecutive lap. During the test, in order to avoid great variations of pedalling frequency (Vped = 83 ± 12 rpm), the used gear ratio varied according to Vc (average Vped variation = 83 ± 12 rpm). In order to minimize the wind influence on the positions, the cyclist exercised at the same Vc in all positions, before increasing Vc by 0.5 m s^{-1}. R_T was determined by the measurement of the average external mechanical power of the cyclist, P_{ext}(W) at constant Vc on each lap as follows: $R_T = P_{ext} V\text{c}^{-1}$. P_{ext} was measured by a simple device (Max One, Look SA, Nevers, France). It was made up to a special rear wheel hub connected with a cable (2 mm diameter) to a display unit clamped over the front part of the handlebars' stem. It was light (300 g) and its installation on the bicycle was simple and fast (5 min). The data were collected at a constant Vc (i.e. after the acceleration phase and before the deceleration phase), which was monitored by the cyclist on the screen of the unit display. The validity of Vc determined by the device was tested in field conditions prior to the investigation from different timed tests performed on the track. Before each P_{ext} measurement, an initialization procedure of the Max One was performed according to the manufacturer's recommendations. It consisted of a free wheel moment of 10 s, which refers to a period where the cycle rolls with no input torque from the rider. It must be pointed out that in the experimental conditions, Va is the component of the air speed acting along the direction of motion. Obviously, in calm air, $Va = Vc$ ($Vw < 1\ \mathrm{m\ s^{-1}}$) and:

$$R_T = P_{ext}\, Vc^{-1} \tag{2}$$

According to equation 1:

$$R_T = 0.5 \rho A C_d Vc^2 + C_r m\, \mathbf{g} \tag{3}$$

with the two constants a and b:

$$a = 0.5 \rho A C_d, \text{ and} \tag{4}$$

$$b = C_r m\, \mathbf{g} \tag{5}$$

$$R_T = a Vc^2 + b \tag{6}$$

In the course of R_T measurements on the four positions, it is possible to determine the AC_d values for every position according to equation 4 ($AC_d = a/0.5\ \rho$) from the slope a of equation 6.

Assuming that the effect of air humidity is negligible (Capelli *et al.* 1993, Di Prampero *et al.* 1979), in the experimental conditions of this study, ρ is then given by:

$$\rho = \rho_0\ (P_B/760)(273/T) = 1.210\ \mathrm{kg\ m^{-3}} \tag{7}$$

where, ρ_0 (1.27 kg m^{-3}) is the density of dry air at 273 K and 760 mmHg (101.3 kPa).

2.3. *Description of the measurement device*

The P_{ext} measurement is performed through a torsion shaft placed in a hub (230 g) especially designed for the rear wheel. When the free wheel drives the hub during the pedalling cycle, the shaft exhibits a rotational deformation in response to torsional loading. The force moment (N m) is quantified through a strain gauge, which assesses the torque applied to the shaft. The angular velocity (rad s^{-1}) is measured four times per wheel revolution by determining the time for the wheel (through a sensor on the wheel) to move through a 10° arc. The power expressed in watts represents the product of the force moment and the angular speed. Information is transmitted to the display unit via the small cable fixed on the bicycle tubes. The algorithm that determines P_{ext} includes the following stages: (1) four samples were collected per wheel revolution, and (2) P_{ext} was the average during eight consecutive revolutions.

2.4. *Calibration of the device*

Before the experiment, a test procedure of the device was conducted. To determine the validity and the reproducibility of the P_{ext} determined by the Max One, P_{mo}(W), two independent investigations were conducted in the laboratory on a treadmill (Gymrol, Super 2500, Tecmachine SA, Andrézieux-Bouthéon, France). Before the investigations, the subjects were weighed (accuracy 200 g) with their personal road bicycles equipped with the Max One device. The inflation pressure of the tyres was 7 bars.

2.4.1. *Validity*: In order to test the validity of P_{mo}, the 12 subjects performed an exertion stage of 1 min duration, on slopes progressively increasing from 1 to 14%

with a 1% increment between each stage. The treadmill speed (corresponding to Vc) was fixed at 4.72 m s^{-1} in order that the subjects performed the exercise with an optimal Vped of 60 rpm (the gear ratio used on the bicycles was equal to 4.72 m per one crank revolution). This V_{ped} was previously determined by all the subjects according to an exercise performed uphill. At each stage, the average P_{mo} was measured and compared to the average reference power, P_{ref}(W). P_{ref} was determined by calculating the rate of change of mechanical energy content of the cyclist plus bicycle (P_{pot}) and the power to overcome the rolling resistance (P_{Rr}).

$$P_{ref} = P_{pot} + P_{Rr} \tag{8}$$

$$P_{ref} = m\,g Vc \sin\alpha + Vc\, C_r\, m\, g \cos\alpha \tag{9a}$$

$$P_{ref} = m\,g\, Vc(\sin\alpha + C_r \cos\alpha) \tag{9b}$$

where α (°) is the slope of the treadmill (α determined from trigonometric measurements with an accuracy of 0.05%) and Vc sin α (m s^{-1}) is the vertical speed.

A C_r value of 0.004 was determined according to the pneumatic type (Tubeless tyre, Corsa Cx, 22 mm, 220 g) and the rolling surface was linoleum (Gross *et al.* 1983, Kyle and Burke 1984, Kyle and Edelman 1975, Ménard 1992). The kinetic power was not taken into consideration because the kinetic energy variations are negligible during the pedalling cycles (Kyle 1988).

The data collection began after 15 s of exercise in order to perform the measurement at a constant Vc. Between each stage, the initialization procedure of Max One was performed. The small width of the treadmill (0.05 m) allowed only rectilinear bicycle displacements on the tread (i.e. lateral displacements were negligible) and during the experiment, the frontal bicycle position on the treadmill was controlled by a visual mark placed on the treadmill subframe. The regularity of Vc was controlled by an operator on a display unit. A correlation analysis was used to determine links between: (1) P_{ref} and P_{mo}, and (2) P_{ref} and the power difference ($P_{mo} - P_{ref}$).

Significant correlations were observed between P_{ref} and P_{mo} ($r = 0.98$, $p < 0.001$) (figure 1) and between P_{ref} and ($P_{mo} - P_{ref}$) ($r = -0.75$, $p < 0.001$). These results indicated that from 151 W, P_{mo} was progressively underestimated by 0.24 W per one additional developed watt and was progressively overestimated from 151 W to 0 W. Thus, the device determined a systematic measurement error that could be due to the strain gauge properties. This determined a progressive loss of linearity of force moment with the increase of the provided power (P_{mo} = force moment × angular speed). However, from the results in this study, the data collected by the device can be corrected (according to the equation in figure 1). It must be emphasized that the strain gauge properties can vary between equally designed elements and, thus, the correction cannot be done for every Max One.

2.4.2. *Reproducibility*: Two subjects (weight = 69.6 kg and 64.6 kg, height = 1.75 m and 1.77 m) participated to test the reproducibility of the device. P_{mo} was measured twice in the same experimental conditions, interrupted by a 30 min recovery period. To eliminate possible Vc differences between the two measurement series, R_T ($R_T = P_{mo} Vc^{-1}$) opposing subject displacement on each slope was compared to determine the reproducibility of P_{mo}. No significant difference between the two paired sets of data was observed by applying the Wilcoxon matched-paired test for

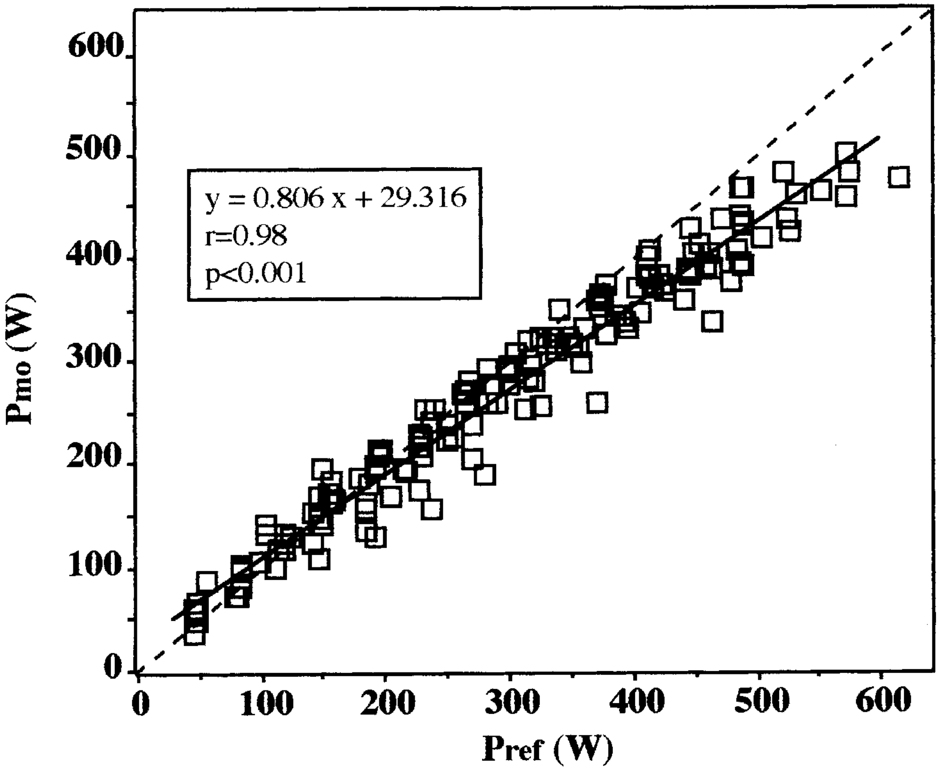

Figure 1. Correlation between the power measured with the Max One (P_{mo}) and the reference power (P_{ref}) determined by calculating the rate of change of mechanical energy content of the cyclist plus bicycle (P_{pot}) and the power to overcome the rolling resistance (P_{Rr}). The dotted line represents the identity line.

non-parametric data. The average absolute measurement error observed between the two tests was 3.2%.

2.5. *Statistical analysis*

For each position, AC_d depends on the slope of the function $R_T - Vc^2$. Thus, to determine whether the position had an effect on AC_d, the R_T/Vc^2 ratios were analysed by a 1-way (position) analysis of variance (ANOVA) with repeated measures. A Fisher *post-hoc* test was used to identify significant differences between the four positions. Significance was established at the $p<0.05$ level.

3. Results

The regression between R_T and Vc^2 in UP, DP, AP and OP are the following (figure 2):

$$-R_T\,(\mathrm{UP}) = 0{\cdot}181\; Vc^2 + 2{\cdot}795\; (r = 0{\cdot}93) \tag{10}$$

$$-R_T\,(\mathrm{DP}) = 0{\cdot}167\; Vc^2 + 1{\cdot}257\; (r = 0{\cdot}90) \tag{11}$$

$$-R_T \text{ (AP)} = 0{\cdot}159\ Vc^2 + 2{\cdot}518\ (r = 0{\cdot}91) \tag{12}$$

$$-R_T \text{ (OP)} = 0{\cdot}131\ Vc^2 + 1{\cdot}242\ (r = 0{\cdot}95) \tag{13}$$

For all the positions R_T increased significantly as a function of Vc^2 ($p<0.001$). An ANOVA showed that the position had a significant effect on the R_T/Vc^2 ratio ($p<0.001$) and thus, on AC_d. The R_T/Vc^2 ratios were significantly different between all the positions ($p<0.05$) except between DP and AP. The AC_d values calculated according to equations 4, 10, 11, 12 and 13 were: AC_d(UP) = 0.299 m^2, AC_d(DP) = 0.276 m^2, AC_d(AP) = 0.262 m^2 and AC_d(OP) = 0.216 m^2. Figure 3 presents the changes in AC_d between UP and other positions (expressed as a percentage).

4. Discussion

In the present study, AC_d was determined with a simple device in real cyclist locomotion (the cyclist was in full exercise) in four different positions (UP, DP, AP and OP). The most important finding was the significant AC_d changes observed between the positions. Moreover, as expected, OP was associated with the lowest AC_d. For all the positions, the correlation coefficients of the functions $R_T - Vc^2$ ranged from 0.90 to 0.95 ($p<0.001$) (figure 2). They are similar to those obtained in

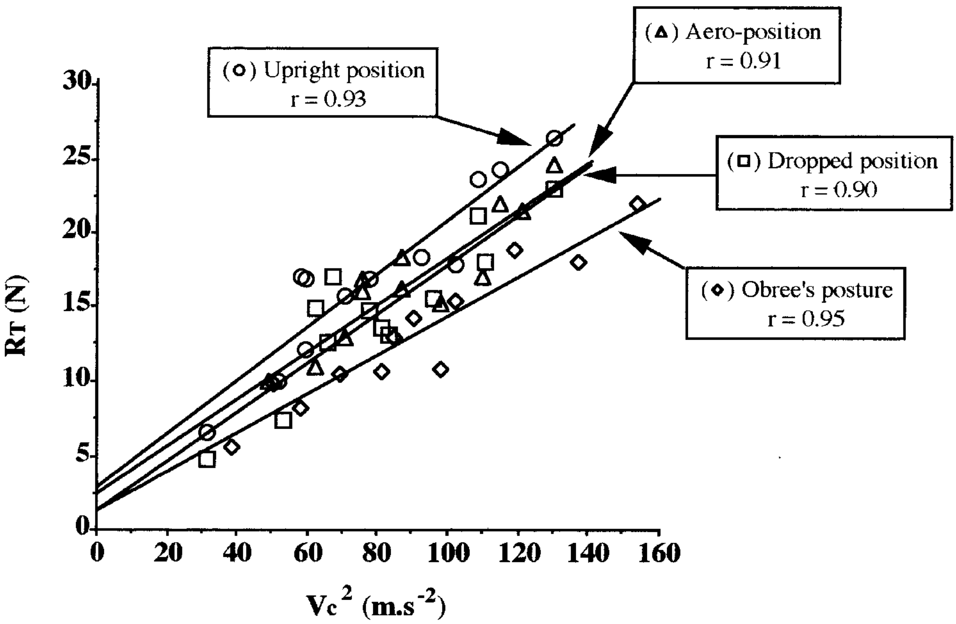

Figure 2. Evolution of the total resistance opposing motion, R_T(N) as a function of the squared cyclist speed, Vc(m s^{-1}) in the four rider positions. For each position, the effective frontal area, AC_d (m^2) depends on the slope of the function $R_T - Vc^2$ and then, on the R_T/Vc^2 ratio. The R_T/Vc^2 ratios were significantly different between all the positions ($p<0.05$) except between the dropped position and the aero-position.

previous studies (Pugh 1974, Davies 1980, Di Prampero *et al.* 1979, Capelli *et al.* 1993).

4.1. *Comparisons of* AC_d *values according to the different measurement techniques*
Table 1 summarizes the AC_d values according to the four positions measured in the present and in the previous studies. In the present experiment, AC_d in UP (0.299 m^2) was lower (−23%) than reported in previous studies (Gross *et al.* 1983, Kyle and

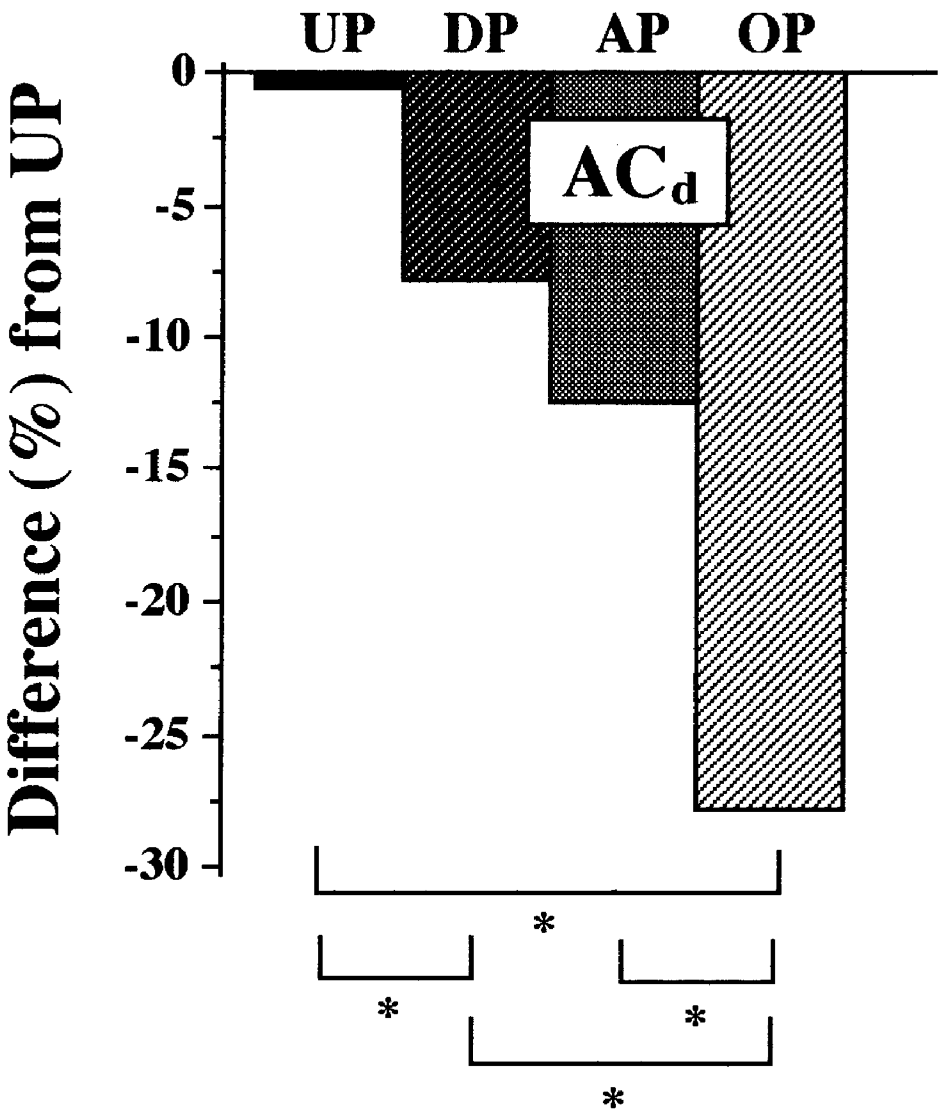

Figure 3. Changes in effective frontal area, AC_d (m^2) between UP and other positions expressed in percentage (%) (UP= upright position, DP= dropped position, AP= aero position, OP= Obree's position). In this figure, UP (reference position)= 0%. *:significant difference at $p<0.05$ (statistical analysis performed on the non-transformed data).

Table 1 Effective frontal area AC_d (m^2) according to upright position (UP), dropped position (DP), aero-position (AP) and Obree's position (OP) in previous studies and in the present study. When the authors reported AC_d changes in percentage (%) between the positions (and when the % are calculated between the positions, in italics), the differences are reported in the table with a reference position (ref). In two investigations (Ménard 1992, Ménard *et al.* 1990) the cyclist used an aero-bicycle in AP position.

Studies	UP	DP	AP	OP
Kyle *et al.* (1973) (deceleration measurement)	ref	−13%		
Pugh (1974) (indirect method)		0.331		
Kyle and Edelman (1975) (deceleration measurement)	0.387 *(ref)*	0.272 *(−29.7%)*		
Di Prampero *et al.* (1979) (dynamometric technique)		0.308		
Davies (1980) (indirect method)		0.280		
Gross *et al.* (1983) (deceleration measurement)	0.39 *(ref)*	0.316 to 0.272 *(−19 to −30%)*		
Kyle and Burke (1984) (wind tunnel)	ref	−19.5%		−28.2% (hill descent position)
Kyle (1989) (wind tunnel)		ref	−15%	
Ménard *et al.* (1990) and Ménard (1992) (wind tunnel)		0.370 *(ref)*	0.260 to 0.191 *(−30 to−48%)*	
Capelli *et al.* (1993) (dynamométric technique)		0.251		
Present study	0.299 *(ref)*	0.276 *(−7.8%)*	0.262 *(−12.4%)*	0.216 *(−27.8%)*

Edelman 1975). However, the value of 0.39 m^2 (Gross *et al.* 1983) was measured with a touring bicycle, the body position of the subject being more vertical than the position of our cyclist. AC_d in DP (0.276 m^2) was similar to those reported in previous studies (Capelli *et al.* 1993, Ménard 1992, Ménard *et al.* 1990, Gross *et al.* 1983, Davies 1980, Di Prampero *et al.* 1979, Kyle and Edelman 1975, Pugh 1974) ranging from 0.251 to 0.370 m^2. The value of 0.370 m^2 was reported in a wind tunnel (Ménard 1992) for a professional cyclist with upper limbs outstretched. The value of 0.251 m^2 (Capelli *et al.* 1993) was obtained with an aerodynamic bicycle and lenticular wheels involving a significant reduction of AC_d, estimated between 15 and 26% (Capelli *et al.* 1993, Kyle and Burke 1984). In AP, AC_d (0.262 m^2) was slightly higher than the range of values (0.260 to 0.191 m^2) reported by Ménard (Ménard 1992, Ménard *et al.* 1990), which had been determined on subjects riding an aerodynamic bicycle. To the best of our knowledge, in OP, no study allows the comparison with the AC_d value found in this study.

The AC_d variability observed for a given position between the different studies could be explained first, by the body position of cyclists on the bicycle and second, by the equipment. However, the morphology of subjects and the measurement method used to determine AC_d, also must be taken into account. The projected frontal area is correlated with the size of the rider (Kyle *et al.* 1973) and C_d depends on the geometric shape of the rider. Indeed, in UP in a wind tunnel, Kawamura (1953) reported a C_d (0.992) that was 5% lower than that (1.042) obtained by Kyle (1979) in the same position. In the wind tunnel measurements (Kawamura 1953, Kyle and Burke 1984, Ménard 1992, Nonweiler 1956, Ménard *et al.* 1990) and in the previous field methods, the dynamometric technique (Chandler and Chandler 1910, Di Prampero *et al.* 1979, Capelli *et al.* 1993) and the deceleration method (Gross *et al.* 1983, Kyle 1979, Kyle *et al.* 1973, Kyle and Edelman 1975), the measurements were not performed on cyclists in a real situation of cycling locomotion. The dynamometric technique (used for towing a cyclist at different *V*c) could involve an air turbulence set up by the moving car, which could modify the measurements. In the indirect measurement methods (Davies 1980, Pugh 1974) the determination of AC_d is difficult and, thus, can give rise to measurement errors. Therefore, in these experimental conditions the drag forces could be different from those occurring when the cyclists are in full exercise. In this study, the method used was easy to implement. After a system calibration procedure the AC_d determination is possible routinely on cyclists in a real situation of cycling locomotion.

4.2. *Changes in* AC_d *between the different positions*

Figure 3 shows that, in the present study, as compared to UP, in DP, AP and OP the significant reductions of AC_d were 7.8%, 12.4% and 27.8%, respectively. These results indicate that the more the trunk was close to the horizontal position the more AC_d decreased. The AC_d decrease in DP was lower than the AC_d decreases (13 to 30%) observed in the previous investigations (Kyle *et al.* 1973, Kyle and Edelman 1975, Gross *et al.* 1983, Kyle and Burke 1984). It may be due to the position adopted in UP by our cyclist that determined a low AC_d (0.299 m^2) as compared with previous studies (Kyle and Edelman 1975, Gross *et al.* 1983). The 12.4% AC_d decrease observed in AP as compared to UP is in line with the study of Kyle (1989) conducted in a wind tunnel. However, larger AC_d decreases in AP have been reported (30 to 48%) on subjects riding an aero-bicycle (Ménard 1992, Ménard *et al.* 1990).

In this study, the AC_d in AP was 4.6% lower than in DP, but the difference was not significant. This lack of significant difference may be explained by the fact that the sensitivity limit of the measurement device used was reached (4.6% difference between the two positions versus 3.2% reproducibility). As compared to DP, the AC_d decrease in AP could be associated with: (1) a lower lateral distance between the two upper limbs that determines a decrease of *A*. Indeed, when the elbows are progressively pulled inward, that streamlines the body (Kyle 1989) and (2) a different forearms inclination versus the horizontal axis (with no change in trunk flexion). Indeed, according to Hoerner (1965), the C_d of a cylinder increases as a function of the sinus cube of the angle formed by the axis of the cylinder and the horizontal axis.

OP determined a 27.8% lower AC_d as compared to UP. This is in keeping with the difference (28.2%) reported by Kyle and Burke (1984) between UP and a huddled up position where the rider was in the hill descent position, the hands on the centre of the upper handlebars, the chin resting on the hands. The high reduction of AC_d in OP (15.4%) as compared to AP was determined by an optimal trunk flexion (the axis of the trunk was parallel to the horizontal axis) and the forearms tucked on the arms.

In the present study, aerodynamic friction measurements were obtained with a simple device in real cyclist locomotion. The results obtained showed that aerodynamic measurements depend on the cyclist position and on the measurement conditions and techniques. Data from the real cyclist locomotion condition confirm that Obree's position provides substantial aerodynamic advantages. However, it seems important to take into account the disadvantages that could be involved in this position. Indeed, OP determines both a great trunk flexion close to the horizontal plane and a forearms position in support under the chest that could be associated with significant physiological changes. Future investigations could determine whether OP has significant effects on ventilatory and metabolic variables.

4.3. *Rolling resistance*

*R*r represents the friction energy losses due to the rotating parts of the bicycle and to the contact between the wheels and the terrain. It depends substantially on the tyre inflation pressure, on the characteristics of the tyres and of the terrain (Whitt 1971, Kyle and Burke 1984) and is proportional to the overall weight (subject plus bicycle). According to previous studies (Capelli *et al.* 1993, Davies 1980, Di Prampero *et al.* 1979, Pugh 1974), the term $a_1 V\mathrm{c}$ could be neglected in *R*r equation. As a consequence, *R*r does not depend on *V*c. Thus, according to equation 6 and from the constants of equations 10, 11, 12 and 13 (figure 2), it is possible to determine the *R*r values for every position. In UP, DP, AP and OP the values of *R*r were 2.79, 1.25, 2.51 and 1.24 N, respectively. The small *R*r differences observed between the series may be explained by the limit of the device sensitivity. Dividing the average *R*r value (1.95 ± 0.81 N) by the total mass of subject plus bicycle (equation 5), the average C_r was 0.0030. The average values of *R*r and C_r were of the same order as values reported by Capelli *et al.* (1993) on the Vigorelli velodrome (Milan, Italy) with traditional wheels (*R*r = 2.43 N and C_r = 0.0031, tyre pressure = 10–11 bars, total mass = 84 kg). Higher *R*r and C_r values were reported (Pugh 1974) on a runway at the Handley Page aerodrome (*R*r = 6.9 N and C_r = 0.0081, tyre pressure = 6.3 bars, total mass = 86 kg) and (Di Prampero *et al.* 1979) on the Monza (Italy) car track (*R*r = 3.2 N and C_r = 0.0046, tyre pressure = 7 bars, total mass = 70 kg). These results suggest that the average *R*r determined in this study is in line with previous studies. Furthermore, they support the findings of Capelli *et al.* (1993) who reported that *R*r on a velodrome was lower than *R*r on a macadam track.

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References

Capelli, C., Rosa, G., Butti, F., Ferretti, G., Veicsteinas, A. and Di Prampero, P. E. 1993, Energy cost and efficiency of riding aerodynamic bicycles, *European Journal of Applied Physiology*, **67,** 144–149.

Chandler, N. R. and Chandler, C. H. 1910, Tractive resistance to cycling, *Cycling*, **9,** 20th July, 132.

Davies, C. T. M. 1980, Effect of air resistance on the metabolic cost and performance of cycling, *European Journal of Applied Physiology*, **45,** 245–254.

Di Prampero, P. E. 1986, The energy cost of human locomotion on land and in water, *International Journal of Sports Medicine*, **7,** 55–72.

Di Prampero, P. E., Cortili, G., Mognoni, P. and Saibene, F. 1979, Equation of motion of a cyclist, *Journal of Applied Physiology*, **47,** 201–206.
Gross, A. C., Kyle, C. R. and Malewicki, D. J. 1983, The aerodynamics of human-powered land vehicles, *Scientific American*, **249,** 126–134.
Health, B. and Carter, J. 1967, A modified somatotype method, *American Journal of Physical Anthropology*, **27,** 57–74.
Hoerner, S. F. 1965, Traînée de pression (Chapitre III), in Gauthier-Villars (eds), *Résistance à l'avancement dans les fluides*, (Paris), 37–68.
Kawamura, T. M. 1953, Wind drag of bicycles, Report No. 1, Tokyo University, Tokyo, November.
Kyle, C. R. 1979, Reduction of wind resistance and power output of racing cyclists and runners travelling in groups, *Ergonomics*, **22,** 387–397.
Kyle, C. R. 1988, The mechanics and aerodynamics of cycling, in E.R. Burke and M.M. Newsom (eds), *Medical and Scientific Aspects of Cycling* (Human Kinetics, Champaign, IL), 235–251.
Kyle, C. R. 1989, The aerodynamics of helmets and handlebars, *Cycling Science*, **1,** 22–26.
Kyle, C. R. and Burke, E. R. 1984, Improving the racing bicycle, *Mechanical Engineering*, **September**, 34–45.
Kyle, C. R. and Edelman, W. E. 1975, Man-powered vehicle design criteria, *Proceedings of the Third International Conference on Vehicle System Dynamics* (Swets and Zeitlinger, Amsterdam), 20–30.
Kyle, C. R., Crawford, C. and Nadeau, D. 1973, Factors affecting the speed of a bicycle, Engineering Report No. 73-1, California State University, Long Beach, CA, 2 November.
Ménard, M. 1992, L'aérodynamisme et le cyclisme, in *Jornadas Internacionales sobre Biomecanica del Ciclismo, Tour 92*. (Centro de estudios e investigaciones tecnicas de gipuzkoa, Donostia San Sebastian).
Ménard, M., Blanche, C. and Niepceron, G. 1990, Contribution à l'amélioration des performances du coureur cycliste, *Institut Aérotechnique de Saint-Cyr*, Conservatoire National des Arts et Métiers Paris, 288.
Nonweiler, T. 1956, Air resistance of racing cyclists, Cranfield College of Aeronautics Report, Cranfield, UK, **106,** 1–9.
Pugh, L. G. C. E. 1974, The relation of oxygen intake and speed in competition cycling and comparative observations on bicycle ergometer. *Journal of Physiology (London)*, **241,** 795–808.
Whitt, F. R. 1971, A note on the estimation of the energy expenditure of sporting cyclists, *Ergonomics*, **14,** 419–424.

Appendix: Glossary of abbreviations.

A	Projected frontal area of the BRC (m^2)
AC_d	Effective frontal area (m^2)
AP	Aero position on the bicycle
BRC	Bicycle-rider combination
C_d	Aerodynamic drag coefficient of the BRC
C_r	Rolling coefficient
DP	Dropped position on the bicycle
$\boldsymbol{g}$	Acceleration due to gravity (9.81 m s^{-2})
m	Mass of subject+ bicycle (kg)
OP	Obree's position on the bicycle
P_B	Barometric pressure (mmHg)
P_{ext}	External mechanical power of the cyclist (W)
P_{mo}	External mechanical power determined by Max One (W)
P_{pot}	Potential power (W)
P_{ref}	Reference power (W)
P_{Rr}	Power to overcome the rolling resistance (W)
Ra	Aerodynamic drag of air (N)

Rr	Rolling resistance (N)
R_T	Total resistance opposing motion of a cyclist (N)
T	Temperature (°)
UP	Upright position on the bicycle
Va	Air speed opposing the motion (m s^{-1})
Vc	Cyclist speed (m s^{-1})
Vped	Pedalling frequency (rpm)
Vw	Wind speed (m s^{-1})
α	Slope of the treadmill (°)
ρ	Air density (kg m^{-3})
ρ_0	Density of dry air (1.27 kg m^{-3})