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Optimal cycling time trial position models: Aerodynamics versus power output and metabolic energy

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ABSTRACT

The aerodynamic drag of a cyclist in time trial (TT) position is strongly influenced by the torso angle. While decreasing the torso angle reduces the drag, it limits the physiological functioning of the cyclist. Therefore the aims of this study were to predict the optimal TT cycling position as function of the cycling speed and to determine at which speed the aerodynamic power losses start to dominate. Two models were developed to determine the optimal torso angle: a 'Metabolic Energy Model' and a 'Power Output Model'. The Metabolic Energy Model minimised the required cycling energy expenditure, while the Power Output Model maximised the cyclists' power output. The input parameters were experimentally collected from 19 TT cyclists at different torso angle positions (0–24°). The results showed that for both models, the optimal torso angle depends strongly on the cycling speed, with decreasing torso angles at increasing speeds. The aerodynamic losses outweigh the power losses at cycling speeds above 46 km/h. However, a fully horizontal torso is not optimal. For speeds below 30 km/h, it is beneficial to ride in a more upright TT position. The two model outputs were not completely similar, due to the different model approaches. The Metabolic Energy Model could be applied for endurance events, while the Power Output Model is more suitable in sprinting or in variable conditions (wind, undulating course, etc.). It is suggested that despite some limitations, the models give valuable information about improving the cycling performance by optimising the TT cycling position.

1. Introduction

In order to minimise the aerodynamic drag, cyclists adopt a time trial (TT) position (often called the 'aerodynamic position'). The TT handlebars allow the rider to adopt this aerodynamic position, resulting in a decreased frontal area and hence aerodynamic drag experienced by the rider. A reduction in aerodynamic drag of approximately 35% is found between an upright position and a TT position (Hennekam, 1990). In addition, Underwood et al. (2011) showed with wind tunnel experiments that in a TT position the total aerodynamic drag is strongly influenced by the torso angle. A difference in drag area of approximately 16% was found for torso angles between 2 and 20°. Moreover, Garcia-Lopez et al. (2009) showed a significant decrease in aerodynamic drag of about 14% when the height of the TT handlebars was lowered. Kyle (2003) also stated that in general the aerodynamic drag is minimal with an almost flat back. From these findings it can be concluded that cyclists should adopt an almost flat (0°) torso angle position to minimise the aerodynamic drag.

However, along with the drag the cyclists peak power output decreases with lower torso angle (Fintelman et al., 2013; Gnehm et al., 1997; Grappe et al., 1997; Jobson et al., 2008). For instance a reduction of 14% peak power output was recorded between an upright (24°) and flat (0°) torso angle TT position (Fintelman et al., 2013). It is suggested by Gnehm et al. (1997) that this peak power output reduction could be related to: (1) muscles not working in their optimal range, (2) a difference in muscle recruitment, (3) greater muscular fatigue, (4) increased pressure on shoulder griddle, neck and arms, and (5) increased adductor activation to keep the leg movement in the sagittal plane due to the extreme hip angles, or a combination of these factors. These experiments imply that cyclists should not adopt an almost flat position.

Clearly there are two conflicting constraints, with aerodynamics requiring a flat position and biomechanics favouring a more upright position. Therefore it can be inferred that combining the results obtained for aerodynamic drag and peak power in different TT positions, a trade-off can be found between the loss in

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power output and drag as function of cycling speed. This is supported by the energy expenditure (*IE*) which is a function of the workload divided by the gross efficiency (η). The workload to overcome drag decreases with smaller torso angles, while the η also decreases.

In previous literature (Gnehm et al., 1997; Jeukendrup and Martin, 2001; Lukes et al., 2005), suggestions have been made that the aerodynamic gains outweigh the loss in peak power output for TT cyclists. However, these statements are based on elite TT cycling speeds, e.g., >45 km/h (Gnehm et al., 1997). Contrary, Underwood et al. (2011) have estimated the optimal cycling position for a relative wind speed of 40 km/h in terms of power output performance and aerodynamic losses. They introduced a new method to analyse the optimal cycling position, the so-called 'surplus power'. The surplus power was defined as the maximal power output of the cyclist minus the aerodynamic power losses and rolling resistance of the tires with the road. In their study, no consistent results about the optimal position were found, which could be due to the limited number of participants ($n=3$). Nevertheless, they have demonstrated the existence of an optimal torso angle at cycling speeds of 40 km/h.

To the best knowledge of the authors, the speed of the cyclist at which the aerodynamic power loss starts to dominate has not been defined. Therefore the aims of this investigation were to predict the optimal TT cycling position as function of the cycling speed and to determine at which cycling speed the aerodynamic power losses starts to dominate. It has been hypothesised that an optimal torso angle exists for each cycling speed and type of event. In the presented work, the torso angle of non-elite cyclists is optimised by using two mathematical models.

2. Method

Two models were developed to determine the optimal torso angle cycling position for a certain cycling speed: the 'Metabolic Energy Model' and the 'Power Output Model'. The Metabolic Energy Model minimised the required cycling energy, while the Power Output Model maximised the surplus power. The inputs for the models came from experimental data of 19 participants in different torso angle positions, β, from 0° to 24° relative to the ground (Fig. 1). Main input parameters were the cycling speeds ranging between 28 and 40 km/h with increments of 1 km/h and torso angle positions with increments of 0.1°. Output of the models was the optimal torso angle position as function of cycling speed.

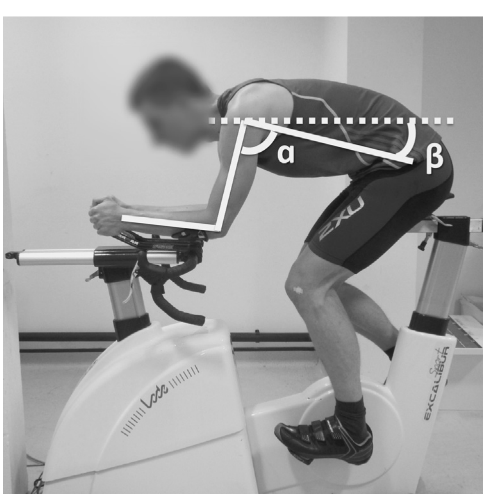

Fig. 1. Definition of torso angle β and shoulder angle a. The torso angles analysed were 0°, 8° ,16° and 24° relative to the ground, while the shoulder angle remained constant. The head position can affect the aerodynamic drag (Lukes et al., 2005). However, for obvious safety reasons cyclists have to maintain their head upright and therefore the current model assumes this position is adopted.

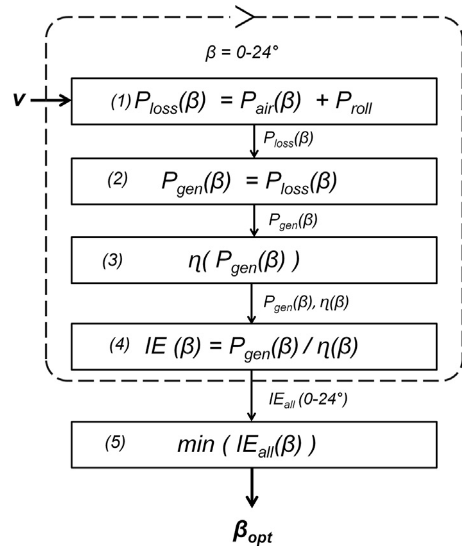

Fig. 2. Metabolic Energy Model step diagram to calculate optimal cycling torso angle as function of the cycling speed.

2.1. Mathematical models

2.1.1. Fundamental principles

During cycling on a flat road, the two main factors of resistance are aerodynamic drag and friction of the wheels with the road. The amount of power loss, P_{loss}, can be estimated by the summation of the aerodynamic drag power losses of the cyclist, P_{air}, and the roll resistance power losses of the wheels, P_{roll},

$$P_{loss} = P_{air} + P_{roll} . \tag{1}$$

The aerodynamic power losses are defined by

$$P_{air} = \frac{1}{2}\rho A C_d v^3, \tag{2}$$

where ρ is the air density, A is the total frontal area of the cyclist and bicycle, C_d is the drag coefficient, and v is the speed of the cyclist relative to the wind. The roll resistance power losses are defined by

$$P_{roll} = \mu m g v, \tag{3}$$

where μ is the roll friction coefficient, m is the mass of the bicycle and cyclist and g is the acceleration due to gravity (9.81 m/s^2).

2.1.2. Models

Metabolic Energy Model. The Metabolic Energy Model minimised the energy expenditure of the cyclist for a given speed. A schematic block scheme of the model is shown in Fig. 2.

In the first step, the cyclists' power loss was calculated by using Eqs. (1)–(3), for every 0.1 degree torso angle between 0° and 24° at a given initial speed and under the given assumptions. Input parameters were the torso angle, cycling speed, mass and frontal area of the individual cyclist. In the second step it was assumed that the cyclist power losses due to drag and rolling resistance were equal to the required power generation of the cyclist; hence constant speed was assumed. This was followed by model step 3, in which for the calculated power generation, the gross efficiency, η, was determined. From the gross efficiency, the corresponding energy expenditure (*IE*) of the cyclist was obtained in step 4. Model steps 1–4 were repeated for all different torso angle positions of the cyclist in the range between 0–24°. Finally, the optimal torso angle, $\beta_{opt,}$ which has the lowest energy expenditure for each given cycling speed, was determined in step 5.

Power Output Model. This model maximised the amount of additional power the participant has available, which could be used for example to accelerate. This so called surplus power is the remainder of the peak power output (*PPO*) in a position with a particular torso angle minus the losses due to the roll resistance and drag in that position, as previous defined by Underwood et al. (2011),

$$P_{surplus} = P_{PPO} - P_{loss}. \tag{4}$$

In Fig. 3, the Power Output Model block scheme is shown. Firstly, the power loss for a given speed in one of the different torso angle positions (0–24°) was calculated by using Eqs. (1)–(3). This was followed by calculating the surplus power in step 2, in which the calculated power losses were subtracted from the recorded PPO of the individual cyclist in the corresponding torso angle position

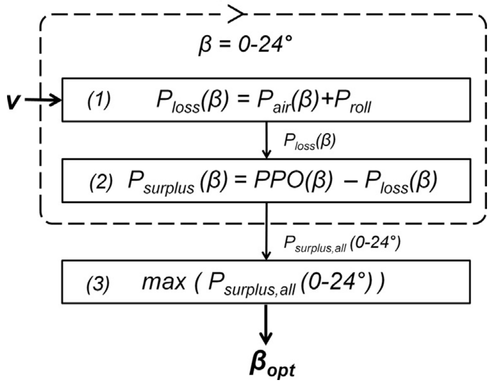

Fig. 3. Power Output Model step diagram to calculate optimal cycling torso angle as function of the cycling speed.

Eq. (4). Model steps 1 and 2 were repeated for all different torso angles ranging between 0° and 24°. Finally the optimal torso angle position, β_{opt}, of the individual cyclist corresponding to the maximal surplus power was determined for each given speed in step 3. It should be noted that only cycling speeds with a positive surplus power for all different torso angle positions were analysed.

2.1.3. Implementation

Both models have been implemented in the commercial software package MATLAB 7.5.0 (MATLAB, The MathWorks Inc., Natick, MA). For each participant the optimal torso angle was determined for every km/h in the range of 28–40 km/h. The optimal torso angles of all participants for each speed were averaged. The cycling speed range was restricted by the maximal power output of the participants. Therefore, outside the 28–40 km/h range the data was extrapolated based on the experimental data, to obtain a speed range of 18–50 km/h. No centripetal forces, acceleration forces or gravitational forces due to uphill or downhill cycling were implemented. This implies the assumption that the cyclist is riding on a flat course, in a straight line and does not accelerate. Also bearing and drive train friction were not implemented, as it accounts only for 1–2% of the total power output (Martin et al., 1998), which was within the workload accuracy of the ergometer. In addition, no wind was acting on the cyclist in the models. Consequently, the speed of the cyclist relative to the wind equals the cycling speed. As a result, all mentioned speeds in this paper could be considered as cycling speeds. Nevertheless, the models are still applicable for head and tail winds, where the relative speed of the cyclist respectively decreases or increases. Contrary, crosswind effects cannot be predicted, as both the relative wind speed and the drag area are altered.

2.1.4. Model input

The *PPO* was calculated for every cyclist. The gross efficiency values, η, of each individual cyclist were interpolated to power and torso angle increments of respectively 1 W and 0.1° torso angle. The P_{loss} was interpolated to obtain a value for every 0.1°. Finally a moving average filter with a window of 10 samples was applied, to avoid model optimisation to the measured torso angle positions.

The total frontal area was the sum of the frontal area of the cyclist, TT bicycle and helmet. The frontal area of the isolated cyclist was estimated by using frontal view photographs in all different torso angle positions. The photos were analysed following the method of Barelle et al. (2010). To account for the TT bicycle and helmet frontal area, 0.086 m^2 was added to the frontal area of the cyclist. The additional frontal area was calculated by taking photographs of an isolated bike and cyclists with and without a TT helmet in all torso angle positions. There was a significant correlation between torso angle and the frontal area (r=0.600, $p<0001$). The total mass included contributions of the cyclist, shoes and TT bicycle. The body mass of each individual cyclist was taken and 8 kg was added to account for the shoes and TT bicycle. A rolling resistance coefficient, μ, of 0.002 (Kyle, 2003) was applied, representing riding on smooth asphalt. It was assumed that the friction coefficient remains constant, irrespective of the cycling speed. The air density, ρ, was set to 1.204 kg/m^3, representing air at 20 °C at sea level. A constant C_d value of 0.86 (Chowdhury and Alam, 2012) was used, independently of the shape and roughness of the cyclist or the cycling speed.

2.2. Experimental data collection

Nineteen healthy male trained competitive triathletes and cyclists, aged between 21 and 52 years participated in the study. The main participants' characteristics are shown in Table 1. All participants completed 4 identical incremental tests on a bicycle ergometer (Lode Excalibur Sport, Lode BV, Groningen, The Netherlands) with TT handlebars (Profile Design Carbon Stryke, Long Beach, United States). The test started with an intensity of 95 W and increased with 35 W every 3 min till exhaustion. The distance between the handlebars (10 ± 1 cm) was replicated from the cyclists' bicycle. The tests were performed in 4 different torso angle positions, β: 0°, 8°, 16° and 24° relative to the ground (Fig. 1). The torso angle was measured with a digital inclinometer (Fisco EN17, Ficso Tools Limited, Essex, UK) with an accuracy of 0.1° and attached to a 1 m stick. The inclinometer was placed on the centre of rotation of the glenohumeral axis and the greater throchanter. The shoulder angle, α, was measured from the cyclists' preferred position and remained constant in all sessions. All participants performed regularly cycling exercise with TT handlebars. The study was approved by the University of Birmingham's Science, Technology, Engineering and Mathematics ethics committee (ERN_12–1223) and participants gave written informed consent at the beginning of the study. The torso angle, power output, oxygen consumption, carbon dioxide exhaled and respiratory exchange ratio (*RER*) were measured throughout the session. At the end of each session a frontal photograph was taken. From the data the gross efficiency, η, was calculated by the formula of Garby and Astrup (1987) and only determined until the *RER* exceeded 1.00.

Table 1
Participant characteristics (mean ± std). Torso length was measured from the centre of rotation of the glenohumeral axis to the centre of rotation of the greater throchanter. The saddle height is the vertical distance between the bottom bracket and the top of the saddle. The torso angle, shoulder angle and Peak Power Output were measured in the participants' preferred cycling position (n=19).

	Value
Age (yr)	34.8 ± 10.7
Height (cm)	181.3 ± 6.0
Body mass (kg)	74.3 ± 8.0
Torso length (cm)	47.5 ± 3.3
Frontal area cyclist at β=0° (m^2)	0.287 ± 0.024
Saddle height (cm)	79.0 ± 3.7
Preferred torso angle, β (°)	11.9 ± 5.6
Shoulder angle, α (°)	90.7 ± 5.3
Peak Power Output (W)	354.1 ± 36.5

3. Results

3.1. Models outcome

Two different models were used to predict the optimal torso angle, β_{opt}. The optimal torso angle was determined for torso angles between 0° and 24°. In Fig. 4 the results of both models and the corresponding confidence intervals (significance level p=0.05) for non-elite TT cyclists are shown for speeds between 28 and 40 km/h. Outside this range, the torso angle was predicted based on extrapolation of the experimental data. It could be seen that the optimal torso angle is dependent on the cycling speed, with torso angle decreasing with increasing speed. Nevertheless, a fully horizontal torso is not optimal. For speeds above 46 km/h, the drag outweighs the power losses. The Power Output Model curve was shifted to a higher speed compared to the Metabolic Energy Model. The Metabolic Energy Model showed a decreased optimal torso angle if the speed of the cyclist increased from approximately 22° at 28 km/h, up to 4° at 40 km/h. The optimal torso angle in the Power Output Model was almost constant in the 28–40 km/h speed range. For speeds between 32 and 39 km/h a torso angle of approximately 17° was found to be optimal, while above 46 km/h the aerodynamic losses outweigh the power losses resulting in an optimal torso angle of 3°. A two-way repeated measures ANOVA examining the effect of cycling speed and model type on the optimal torso angle was conducted. In all statistical tests the significance level was set to p=0.05. There was a statistically significant interaction between the speed and the model type on the optimal torso angle within the subjects $F(4,72)$=23.22, $p<0.0001$. A multiple regression was performed to predict optimal torso angle from a group of anthropometric variables of each participant for cycling speeds between 28–40 km/h, with increments of 3 km/h. Variables included were torso length, body mass, height and frontal area. For the Metabolic

Energy Model, only the frontal area significantly predicted the torso angle for speeds of 28 and 31 km/h ($F(1,17)=9.41$ $p=0.007$, $R^2=0.318$ and $F(1,17)=3.27$ $p=0.088$, $R^2=0.112$). In the Power Output Model analysis, the power output difference between the 24° and 0° torso angle position was added and resulted in the best predictor (R^2 between 0.321 and 0.492, $p<0.01$).

3.2. Experimental data

The mean of the recorded maximal power output of the participants in the 0° and 24° torso angles were 318 W and 369 W respectively. The reduction in *PPO* was found to be approximately 14% (51 W). The calculated power losses due to aerodynamic drag and rolling friction of the wheels on the road for speeds between 28 and 40 km/h are shown in Table 2. For the extreme torso angles, 0° and 24°, the power loss differences were calculated for each speed. The absolute differences between the losses in these two extreme positions are shown in Table 3.

As the aerodynamic power losses are proportional to the cube of the speed, the power loss differences between the extreme values were as well. The mean calculated reduction in drag between the 24° and 0° torso angles was found to be approximately 10%.

The optimal torso angle was mainly determined by aerodynamic drag. At a speed of 24 km/h approximately 13% of the total power losses accounted for rolling resistance, while for 40 km/h it dropped to approximately 5%.

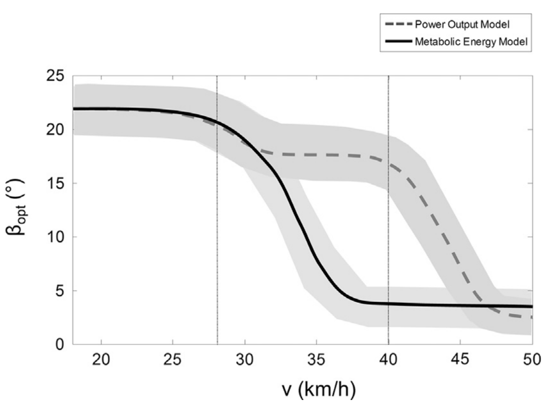

Fig. 4. Optimal torso angle as function of cycling speed with confidence levels with a significance level set on $p=0.05$. For speeds between 28 and 40 km/h the optimal torso angle curves as function of cycling speed are based on the Power Output Model and the Metabolic Energy Model. Outside this range, the optimal torso angle positions are predicted based on extrapolation of the experimental data.

4. Discussion

Two models were developed to predict the optimal torso angle position at different cycling speeds: the Metabolic Energy Model and the Power Output Model. The results showed that the optimal torso angle depends strongly on the cycling speed, with decreasing torso angles at increasing speeds. However, a fully horizontal back is not optimal. At speeds above 46 km/h, the aerodynamic losses outweigh the power output losses, which is in line with previous literature (Gnehm et al., 1997; Jeukendrup and Martin, 2001; Lukes et al., 2005). The Power Output Model and Metabolic Energy Models outputs were not similar. This is not surprising as the fundamental principles underpinning these two models are different. The model type application depends on the type of event. The Power Output Model is more relevant if a cyclist is cycling in a short distance event or need to have additional power available to accelerate, cycle up-hill or is subjected to head or side wind. In these situations, the energy consumption is less dominant. However, the optimal cycling position based on Metabolic Energy Model is more relevant for long distance races. If a cyclist is more efficient, they will save energy which can be used later during the race for like sprinting, change in wind conditions or overall higher performance. If for instance the energy saved riding at 36 km/h in a 3° crouched position compared to a 16° upright position will be used to increase the cycling speed in the crouched position, a time saving of about 3 min will be experienced in case of a 40 km TT under windless conditions. In conclusion, for speeds between 32 and 40 km/h in an endurance event it is advisable to lower the torso despite the fact that the power output in a more aerodynamic position is decreased. In contrast, in sprinting or in variable conditions (wind, undulating course, etc) at these speeds it is more beneficial to ride in a more upright TT position.

Although the models provide a practical general prediction of the optimal torso angle, the authors acknowledge that there are individual differences between the optimal torso angle predictions. Individual differences in position optimisation were also found in the study of Underwood et al. (2011). The multiple regressions analysis has shown that all analysed anthropometric parameters inadequately predict the optimal torso angle. This might be a result of the homogeneity of the participant group. On the other hand, there is no evidence that our sample was not representative of the TT population. Besides participant differences, training in a lower torso angle position can have a positive effect on the power output and oxygen consumption (Peveler et al., 2005; Heil et al., 1997). However, it has been shown that when cyclists adopt more extreme torso angle positions (in particular close to 0°), the physiological performance significantly

Table 2
Mean and standard deviation of the power losses at different cycling speeds ranging between 28 and 40 km/h and in different torso angle positions (0–24°) of all participants ($n=19$). The power losses included contributions of the aerodynamic drag and road friction power losses of each individual participant.

Cycling speed	28 km/h	30 km/h	32 km/h	34 km/h	36 km/h	38 km/h	40 km/h
$P_{loss(0^\circ)}$ (W)	103.7 ± 6.8	125.5 ± 8.2	150.3 ± 9.8	178.4 ± 11.5	209.8 ± 13.5	244.8 ± 15.8	283.5 ± 18.2
$P_{loss(8^\circ)}$ (W)	107.2 ± 6.0	129.9 ± 7.2	155.6 ± 8.6	184.7 ± 10.2	217.3 ± 11.9	253.6 ± 13.9	293.9 ± 16.0
$P_{loss(16^\circ)}$ (W)	110.7 ± 7.2	134.2 ± 8.7	160.9 ± 10.4	191.0 ± 12.3	224.8 ± 14.5	262.4 ± 16.9	304.1 ± 19.5
$P_{loss(24^\circ)}$ (W)	115.2 ± 7.3	139.7 ± 8.8	167.6 ± 10.5	199.1 ± 12.4	234.4 ± 14.6	273.7 ± 17.0	317.3 ± 19.7

Table 3
Mean and standard deviation of the absolute difference of the calculated mean of the power losses in two TT torso angle positions at different speeds of all participants, i.e. 0 and 24° ($n=19$). The total power losses are the total of the aerodynamic drag and road friction power losses.

Cycling speed (km/h)	28	30	32	34	36	38	40
$\Delta P_{loss(0^\circ,\ 24^\circ)}$ (W)	11.6 ± 2.9	14.2 ± 3.6	17.3 ± 4.3	20.7 ± 5.2	24.6 ± 6.1	28.9 ± 7.2	33.7 ± 8.4

drops independently of the cyclists' training position (Fintelman et al., 2013). To investigate the effect of training on the cycling performance, all participants performed one additional incremental test in their preferred position. These experiments demonstrated that in general the participants' maximal power output did not correspond to the cyclists preferred position. Although no training effect was observed in this study, it is possible that training at lower torso angle positions could slightly improve the power output (Jeukendrup and Martin, 2001; Peveler et al., 2005). In particular for cyclists with a relatively large preferred torso angle, the optimal torso angle might decrease at lower speeds. Nonetheless, it can be concluded that anthropometrical differences and training will only have a small effect on the optimal torso angle model predictions.

In the models a constant C_d value was estimated for all participants. It should be noted that the selection of C_d affects the location of the large torso angle decrease in the model output. In previous literature, the drag coefficient in the TT position has been reported in the range of 0.63–0.99 (Chowdhury et al., 2011; García-López et al., 2008; Underwood et al., 2011). It has been shown that the $C_d$value is not constant and the variations complex, which could explain the variation in C_d values between different studies which is therefore difficult to estimate. In this study only the handlebar height was alternated, while the shoulder angle and position of the hands were kept constant. Therefore it could be considered that only a small variation in the flow structures and therefore $C_d$values exists between the different torso angles. Still, these deductions have to be tested either experimentally or numerically by using Fluid Dynamic Simulations.

In conclusion, two models were developed to determine the optimal cycling position as function of cycling speed. A trade-off between the aerodynamic performance and power output is shown. For speeds above 46 km/h the aerodynamic power losses dominates. For lower speeds, the optimal torso angle is dependent on the cycling event. The presented models can be used to advise non-elite cyclists about the optimal torso angle TT position, taking into account aerodynamics and physiology. Future research should attempt to implement the effect of side winds.

Conflict of interest statement

None.

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References

Barelle, C., Chabroux, V., Favier, D., 2010. Modeling of the time trial cyclist projected frontal area incorporating anthropometric, postural and helmet characteristics. Sports Eng. 12, 199–206.
Chowdhury, H., Alam, F., 2012. Bicycle aerodynamics: an experimental evaluation methodology. Sports Eng. 15, 73–80.
Chowdhury, H., Alam, F., Mainwaring, D., 2011. A full scale bicycle aerodynamics testing methodology. Proc. Eng. 13, 94–99.
Fintelman, D., Highton, P., Adams, T., Sterling, M., Hemida, H., Li, F.-X., 2013. Cycling time trial position: torso angle affects metabolic and physiological variables. In: Proceedings of the ECSS Annual Conference 2013. Barcelona.
Garby, L., Astrup, A., 1987. The relationship between the respiratory quotient and the energy equivalent of oxygen during simultaneous glucose and lipid oxidation and lipogenesis. Acta Physiol. Scand. 129, 443–444.
García-López, J., Rodríguez-Marroyo, J.A., Juneau, C., Peleteiro, J., Martínez, A.C., Villa, J.G., 2008. Reference values and improvement of aerodynamic drag in professional cyclists. J. Sports Sci. 26, 277–286.
Gnehm, P., Reichenbach, S., Altpeter, E., Widmer, H., Hoppeler, H., 1997. Influence of different racing positions on metabolic cost in elite cyclists. Med. Sci. Sports Exerc. 29, 818–823.
Grappe, F., Candau, R., Belli, A., Rouillon, J.D., 1997. Aerodynamic drag in field cycling with special reference to the Obree's position. Ergonomics 40, 1299–1311.
Heil, D.P., Derrick, T.R., Whittlesey, S., 1997. The relationship between preferred and optimal positioning during submaximal cycle ergometry. Eur. J. Appl. Physiol. Occup. Physiol. 75 (2), 160–165.
Hennekam, W., 1990. The speed of a cyclist. Phys. Educ. 25, 141.
Jeukendrup, A.E., Martin, J., 2001. Improving cycling performance: how should we spend our time and money. Sports Med. 31, 559–569.
Jobson, S.A., Nevill, A.M., George, S.R., Jeukendrup, A.E., Passfield, L., 2008. Influence of body position when considering the ecological validity of laboratory time-trial cycling performance. J. Sports Sci. 26, 1269–1278.
Kyle, C.R., 2003. Selecting cycling equipment. In: Burke E.R. (Ed.), High-tech Cycling, 2nd ed. Human Kinetics, Leeds, UK (Chapter 1).
Lopez-Minarro, P.A., Andujar, P.S.D., Rodriguez-Garcia, P.L., 2009. A comparison of the sit-and-reach test and the back-saver sit-and-reach test in university students. J. Sports Sci. Med. 8, 116–122.
Lukes, R., Chin, S., Haake, S., 2005. The understanding and development of cycling aerodynamics. Sports Eng. 8, 59–74.
Martin, J.C., Milliken, D.L., Cobb, J.E., McFadden, K.L., Coggan, A.R., 1998. Validation of a mathematical model for road cycling power. J. Appl. Biomech. 14, 276–291.
Peveler, W., Bischop, P., Smith, J., Richardson, M., 2005. Effects of training in an aero position on anaerobic power output. J. Exerc. Physiol. 8, 44–50.
Underwood, L., Schumacher, J., Burette-Pommay, J., Jermy, M., 2011. Aerodynamic drag and biomechanical power of a track cyclist as a function of shoulder and torso angles. Sports Eng. 14, 147–154.