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Aerodynamic performance and riding posture in road cycling and triathlon

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Abstract
Cycling performance is strongly dependent on aerodynamic drag, of which the majority is attributable to the rider. Previous studies have shown the importance of optimising athlete posture on the bicycle for individual time-trial events. This article identifies that performance in road cycling and draft-legal triathlon can be improved through aerodynamic optimisation of the athlete's posture. Nine relevant cycling postures have been studied, and it was found that for road cycling, gripping the hoods with horizontal forearms can reduce the required cyclist power by 13.4%, and for draft-legal triathlon applications, the use of short bar extensions reduced the required power by up to 16.7%. It was also found that lowering the eyes and head increased drag in both drops and triathlon postures. Measurements of the velocity profiles of the wake of a cyclist in four different postures are presented, and it is shown that differences in drag coefficients between postures can be correlated with changes in the wake velocity defect and turbulence intensity distribution.

Keywords
Cycling, triathlon, aerodynamics, posture, performance, positioning, drag, power

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Introduction

The importance of aerodynamics to the performance of elite cyclists is well established[1–5] and widely recognised. For an individual cyclist travelling at 50 km/h, over 90% of his or her output power is expended overcoming aerodynamic drag.[1–3] While the bicycle is a source of drag, the majority can be attributed to the cyclist.[1,6]

The aerodynamic drag of a cyclist has been shown to vary according to the posture of the rider. Four riding postures are most commonly identified in the existing literature: hands on the flat of bars sitting upright (climbing posture), hands on the brake levers in conventional riding posture (hoods posture), traditional racing posture with hands on the curved part of the handlebars (drops posture) and a time-trial posture. The time-trial posture utilises different bicycle geometry and setup to road cycling, which allows the riders to position their arms in front of their torso. Several studies have compared these postures and have found the same relative aerodynamic performance.[1,2,6–8] The time-trial posture has the lowest drag, followed by, in order of lowest to highest drag, the drops posture, hoods posture and climbing posture. The time-trial posture has been shown to offer a drag reduction of 5%–30% over the conventional road racing posture on the drops.[2,5–8]

While the time-trial posture has been shown to be the most aerodynamically efficient form of cycling, subtle variations can be made to this general posture, which can amount up to 10% change in the total drag.[9–12] Such results show that there is significant room for optimisation of a cyclist even within the framework of the general time-trial posture. It logically follows that the posture of road cyclists may be optimised in a similar way.

Road races have many factors that make modelling performance gains more difficult to achieve and reduce the contribution of aerodynamics to overall performance. Road cycling races are mass start events, which means athletes are subject to complex aerodynamic interactions as well as through team tactics. It has been

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shown that a trailing or drafting cyclist can reduce drag by up to 49%.[8,13–18] As such, riders travelling in a large group can travel at well below maximum output. Road races also often include high gradient climbs, where speed is significantly reduced and aerodynamic drag becomes a less significant component of resistance. Road cycling events are also often significantly longer than time-trial or pursuit events, making athlete comfort a more important consideration.

The combined effect of these factors has led to a perception that aerodynamics is a secondary performance factor in road racing events. This has resulted in far less attention to the evolution of road cycling aerodynamics when compared to time-trial racing. However, there are still times during these events when aerodynamics remains vital. In particular, aerodynamics plays a key role in sprint finishes, breaking away from a group, riding on the front of a group and chasing to re-join the peloton. As such, optimising the aerodynamics of a road cyclist's posture can still deliver non-negligible performance benefits to athletes.

Published studies investigating an athlete's riding posture on a conventional road bicycle show that the drops posture reduces drag by up to 12% compared with the hoods posture.[8,19–25] This does not lead to a performance enhancement as it is already the standard racing posture. However, if the athlete crouches to lower the head and torso, drag decreases by a further 4%–19%.[8,9] This being so, there are variations to the established traditional riding posture on the drops of the handlebars that are utilised by athletes during races.

Elite short-course triathlon shares many similarities with road cycling. Since the mid-1990s, drafting has been legal during the cycle leg of elite triathlon at standard and sprint distances. This means that the rules and tactics are similar to road cycling events. Prior to this, triathletes were not allowed to ride close together so as to benefit from interaction effects. This made the ride more of an individual time-trial style race. Drafting restrictions still apply to amateur and long-course triathlon racing. Elite draft-legal events share the same bicycle equipment rules with road cycling, but with one distinct difference: the use of short handlebar extensions is permitted. These bars must not extend beyond the brake levers, making them much shorter than for a typical time-trial setup. This leads to a hybrid between the aerodynamic time-trial posture and a road cycling setup. However, to the authors' knowledge, the aerodynamic performance of such postures has not been previously reported, and perhaps as a result, they are not universally adopted by athletes competing in draft-legal triathlons.

A cyclist, like other ground vehicles, can be classed as a *bluff body* as the flow separates from the cyclist to form an unsteady (turbulent) wake. In addition, unlike most vehicles, a cyclist has a dynamic geometry due to the pedalling motion of the legs. It has been shown that the position of the legs has a profound influence on the flow behaviour and consequently the flow structure in the wake.[26–28] The wake flow topology has been shown to be dominated by the position of the legs in combination with the general human form. However, at present, it is not clear how controllable changes in the rider posture on the bike influence the flow field around the body and the structure of the wake, which in turn influence the overall drag.

While the posture of cyclists in road cycling events will influence their aerodynamics, at present the relationship is not well understood. The purpose of this research is to develop an understanding of the relative aerodynamic performance of common road cycling and draft-legal triathlon postures through a wind-tunnel test programme. It also aims to explain the cause of the identified performance differences of key postures by conducting wake measurements in the wind tunnel. This information will give athletes and scientists guidance with respect to aerodynamic efficiency of riding postures, the sources of aerodynamic drag and the nature of the wake.

Experimental methodology

All testing reported in this article was conducted with approval from the Monash University Human Research Ethics Committee: Project Number CF13/1326 – 2013000679. The investigation was conducted in the Monash University Wind Tunnel. This wind tunnel has a three-quarter open jet test section with nozzle dimensions of $2.6 \times 4\,\text{m}^2$, equating to a blockage of $<9\%$ for a cyclist (including test rig). A constant wind speed of 12.5 m/s (45 km/h) was adopted for all tests. This wind speed was selected as it is typical of race speeds in elite triathlon and road cycling. Cyclist drag force was measured using an air-bearing–type force balance, designed and manufactured by Monash University. The balance consists of two sets of planar air bearings that isolate the axial (drag) force component and a single-axis strain gauge to measure the drag force. A disadvantage of the system is that it is not capable of measuring other force and moment components, such as side force and roll moment, which are relevant to cross-wind analysis. However, the system is very stable under the dynamic loads of a pedalling cyclist. At the selected wind speed, the accuracy of the system is 0.2% of the applied load for a steady axial force.

The results presented in the following sections are the mean of at least two consecutive runs sampled over 30 s. As indicated above, it has been shown that the drag of a cyclist varies with leg position around the crank cycle.[26–28] This variation is also seen in the oscillating drag force during dynamic tests. For this reason, it is necessary to sample over-sufficiently many cycles, such that the mean is effectively independent of the leg start and end positions. At a pedalling cadence of 90 r/min, 30 s corresponds to 45 pedalling cycles. The mean variation in repeatability for a given riding posture was 0.5% for consecutive test runs.

Table 1. Description of riding postures tested covering both cycling and draft-legal triathlon postures.

	Posture and description	Frontal area (m^2)
1	Hands on hoods – reference posture	0.4941
2	Drops – conventional racing posture	0.4720
3	Drops and crouched torso – arms bent to lower torso angle	0.4594
4	Drops and crouched torso with eyes looking down	0.4520
5	Hoods grip – gripping brake hoods with horizontal forearms	0.4365
6	Aerobars – typical ITU draft-legal short aerobars	0.4174
7	Aerobars with head lowered and shoulders shrugged	0.3855
8	Aerobars with eyes looking down	0.4126
9	Aerobars with head tucked between arms	0.3850

ITU: International Triathlon Union.

The cyclist was mounted on a raised ground plane, positioned 400 mm above the true floor, to accommodate the force balance apparatus and reduce the size and effect of the oncoming boundary layer. The wind tunnel has a turbulence intensity of ~1.6% (*Iuvw*) at the centre of the test section. This is relatively high compared to many research wind tunnels but is closer to natural atmospheric conditions, making it more suitable for ground vehicle testing.[29]

All tests were performed with the rider aligned with the flow at a yaw angle of 0° (no cross-wind). While yaw angle is an important consideration in road cycling due to environmental wind, drag is not the only load to consider for non-zero yaw. With the relative wind vector at an angle to direction of motion, side force, roll moment and yaw moment all become significant loads acting on a cyclist and affect the cyclist's dynamics.[30] Their impact on performance, however, is less well understood. At present, the test apparatus used is only capable of measuring axial drag, and so it was decided to confine the investigation to a yaw angle of 0° only for the current set of tests.

A national-level elite athlete riding a road specification bicycle with International Triathlon Union (ITU) legal aerobars was used as the subject for the study. The athlete wore a conventional vented road helmet and a sleeveless triathlon racing skin suit. The bicycle was fitted with low-profile (30 mm) rims. Tests were conducted with pedalling legs to most accurately simulate full cycling dynamics. The bicycle was mounted to the force balance by a set of aerodynamic struts at the rear axle. The front wheel was free with some degree of lateral movement possible. Using only rear struts provides the greatest realism to practical road cycling as it allows some natural movement of the front wheel and minimises upstream aerodynamic interference. Both wheels were on rollers. A timing belt connected the two rollers such that driving the rear wheel from athlete pedalling would also drive the front roller and consequently the front wheel.

Nine different riding postures were selected as representative of athlete riding postures adopted during road cycling and draft-legal triathlon events. These postures were identified from observations of elite competitors in road cycling and triathlon events. The postures are indexed in Table 1 and shown in Figures 1 and 2. They are selected to be representative of postures that may be adopted at stages during competition but not necessarily for an entire race. For example, Postures 4 and 8 require the cyclists to drop their eyes towards the ground and can, therefore, only be maintained intermittently during races.

Postures 1–5 are representative of common road riding postures and so are applicable to both road cycling and triathlon. Postures 6–9 utilise the short draft-legal triathlon style aerobars (as seen in Figures 1 and 2) which are not currently permitted in road cycling races.

Wake velocity field measurements were conducted behind the cyclist for Postures 1, 2, 5 and 6. These were selected as the most important postures for the study. Postures 1 and 2 are the most common postures in terms of practice and the literature and represent the high-drag cases. Posture 5 represents the lowest drag case for road cycling, and Posture 6 represents draft-legal triathlon posture using short aerobars. Velocity field measurements were collected by traversing four-hole dynamic pressure probes (Turbulent Flow Instrumentation (TFI) Cobra Probes) in the wake of the pedalling athlete. The probes are able to measure flow angle, where the angle is within a 45° cone of acceptance. This allows the mapping of three-axis velocity components. The cross-sectional plane was 600 mm (the length of the torso chord) downstream of the rear of the athlete.

To present the drag results in a more tangible form for performance comparison, an equivalent input power requirement was calculated. Martin et al.[31] described a detailed equation of motion for modelling cycling power. This model accounts for all forms of energy in the system. There are five identified power terms affecting cycling resistance: aerodynamic (AT), rolling resistance (RR), wheel bearing (WB), changes in potential energy (PE) and changes in kinetic energy (KE). The potential energy term accounts for changes in altitude due to terrain and the kinetic energy term for changes caused by accelerations. It is stated in its most general form in equation (1). The chain efficiency (E_C) accounts for frictional losses in the chain and driveline

Figure 1. Front view of riding Postures 1–9 as listed in Table 1.

$$P_{TOTAL} = \frac{(P_{AT} + P_{RR} + P_{WB} + P_{PE} + P_{KE})}{E_C} \qquad (1)$$

As power calculations in the present context are for comparative purposes, it is sufficient to assume a constant speed and zero gradient so as to neglect the potential and kinetic energy terms. The model does include the facility for consideration of yaw angles to model relative wind vectors at an angle to the direction of motion. For comparison in this investigation, the effects of environmental wind are neglected such that the nominal ground speed and air speed are equal. This leads to the simplified equation for cycling power shown in equation (2). The physical values used in the power calculations are given in Table 2. These are taken from the original model parameters[31] unless otherwise stated

$$P_{TOTAL} = \frac{(P_{AT} + P_{RR} + P_{WB})}{E_C}$$
$$P_{TOTAL} = \frac{\left[\frac{1}{2}\rho(C_DA + F_W)V_G^3 + \mu(m_1 + m_2)gV_G + V_G(91 + 8.7V_G)10^{-3}\right]}{E_C} \qquad (2)$$

Results

Drag force and power

The force results and calculated power requirement for each posture are presented in Table 3. The reduction in drag and required power for each posture compared to the reference position (Posture 1) can be seen in Figure 3. The highest drag was, as expected, for Posture 1 ($C_DA = 0.343\,\mathrm{m}^2$) and the lowest drag for Posture 7 ($C_DA = 0.283\,\mathrm{m}^2$).

Posture 2 (the traditional drops racing posture) represented only a small saving over Position 1 (hoods posture). However, when a crouch is added, to lower the head and torso, the power requirement drops a further 7% over the standard drops posture with straighter arms. However, the ‘crouch’ posture is somewhat arbitrary; Figures 1 and 2 clearly display the difference between the two. This indicates that drag in the drops posture is sensitive to individual athlete’s riding posture and the angle of the torso and arms.

Posture 5 was found to have a 13.4% reduction in required power over Posture 1 and 10.3% over Posture 2. This represents the most efficient riding posture for road cycling events, with large power savings over more traditional riding postures. Posture 6 (athlete using short aerobars) reduced required power by 15.2% and 12.1% over Postures 1 and 2, respectively. This reduction increased a further 1.5% with the addition of shrugged shoulders and a slight head tuck. The combination of aerobars and shrug yielded the greatest power saving of all postures tested, with a 16.7% reduction over Posture 1. This offers a large performance benefit and shows that triathletes would benefit from the use of such a riding posture compared to standard road postures.

Postures 4 and 8 represent the same body position as Postures 3 and 6, respectively, but with the eyes and

Figure 2. Side profile view of riding Postures 1–9 as listed in Table 1.

Table 2. Physical assumptions and symbols used in power model (equation (2)).

Athlete mass	m_1	70 kg
Bicycle mass	m_2	8 kg
Coefficient of rolling resistance[31,32]	μ	0.005
Aerodynamic resistance factor due to wheel rotation	F_W	0.0044 m^2
Chain efficiency factor	E_C	0.976
Density	ρ	1.2 kg/m^3
Cyclist velocity	V_G	45 km/h 12.5 m/s

Table 3. Drag coefficient area and simulated power required for each posture (see Table 1 and Figures 1 and 2).

Posture	C_DA (m^2)	Power required (W)	Delta C_DA (m^2)	Delta power (W)
1	0.343	430		
2	0.332	417	0.011	13.0
3	0.306	385	0.037	43.9
4	0.321	403	0.022	25.9
5	0.295	372	0.048	56.0
6	0.289	365	0.054	63.6
7	0.283	358	0.060	70.1
8	0.295	372	0.048	56.5
9	0.287	363	0.056	65.1

Delta values are for the change in C_DA and power referenced to Posture 1.

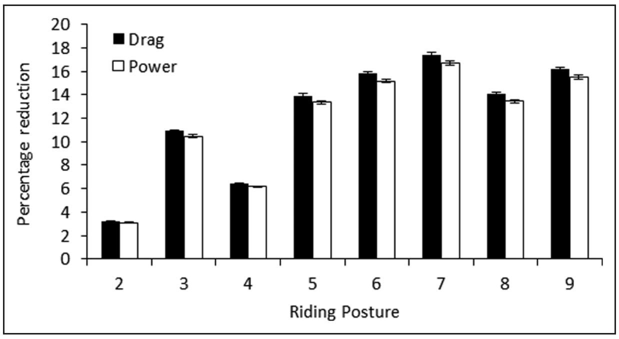

Figure 3. Percentage reduction in required power referenced to Posture 1 (hoods posture) – see Table 1 and Figures 1 and 2.

head lowered (see Figures 1 and 2). In both cases, the lowering of the head resulted in an increase in drag compared to the raised head position; Posture 3 had lower drag than Posture 4 and Posture 6 had lower drag than Posture 8. This refutes the perceived aerodynamic advantage assumed for the common practice of athletes dropping their head in periods of high intensity. It is possible that this effect is caused by the presentation of a more bluff head/helmet to the flow and may be associated with the geometry of the test helmet. This would induce greater flow separation over the head, shoulders and upper back than with the head and eyes looking ahead of the rider. Posture 9 is an aggressive case with the head tucked down between the arms and below the line of the shoulders. This posture was tested to study the effect of more extreme postures, irrespective of whether their adoption is realistic, since such a posture could not be held for any great duration in practice. Despite the head being dropped well below the line of the shoulders, the frontal area of Posture 9 is not significantly lower than that of Posture 7. Power required was also greater than Posture 7. In addition to the similar frontal area, this may be the result of disruption in the flow between the arms that normally flows under the torso and out over the hips and between the legs.[24–26]

Road cycling applications

The use of aerobars is legal in triathlons; however, it is prohibited from all forms of mass start road and track cycling events. The postures in this study that do not use aerobars have been selected as representative of road cycling riding postures. As such, the power savings for Postures 2-5 presented in Table 3 and Figure 3 are applicable to road cycling applications.

Simulated time saving

Using the described power model, it is possible to model a time saving for each position, given a specified race distance and a constant output power. This is a simplification of cycling dynamics but helps to highlight the impact of aerodynamic drag on performance. For a flat course with little wind and a cyclist riding solo, it provides a reasonable indication of performance improvement. Simulated time saving for each posture (referenced to Posture 1) of an elite-level triathlete competing in a standard distance triathlon with a 40-km ride and a constant power output of 300 W is presented in Figure 4.

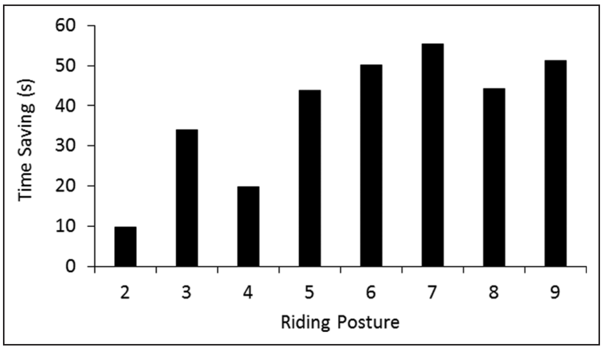

Figure 4. Simulated time saving for each posture relative to Posture 1 (see Table 1 and Figures 1 and 2) modelled on 40 km standard distance triathlon cycle leg with a constant mean power output of 300 W.

Wake of a dynamic cyclist

Wake surveys were conducted to map the velocity behind the cyclist for Postures 1, 2, 5 and 6. These were selected as the most important postures. Postures 1 and 2 are reference conditions and the most common postures in practice and the literature, and provide insight into the high-drag cases. Posture 5 is the lowest drag posture identified for road cycling, and Posture 6 is an example of a draft-legal triathlon posture adopting short aerobars. Figure 5 shows the streamwise velocity profile for each of the four postures. Each plot shows only half of the wake, given the symmetry of the flow for the time-averaged dynamic wake. Consistent with the literature,[24–26] the measurements demonstrate that the flow regime associated with a cyclist is highly turbulent and has large regions of separated flow. As such, the cyclist is appropriately characterised as a bluff body. It also highlights the potential for improvement in a cyclist's aerodynamics by reducing viscous losses.

In Figure 5, it can be seen that the wakes of Postures 1 and 2 have larger areas of low velocity compared to Postures 5 and 6. Figure 6 shows a comparison wake profile generated by subtracting the velocity field of the highest drag case (Posture 1) from the fields of the other three, highlighting the main areas of difference in the wake.

On comparison, the body position of Postures 1 and 2 is similar (see Figures 1 and 2); however, differences are evident in the wake distribution. The riding position of Posture 2 has the head and shoulders slightly lower in height, and an associated decrease in velocity defect can be seen in this region. However, Posture 2 exhibits a higher velocity defect at shoulder height

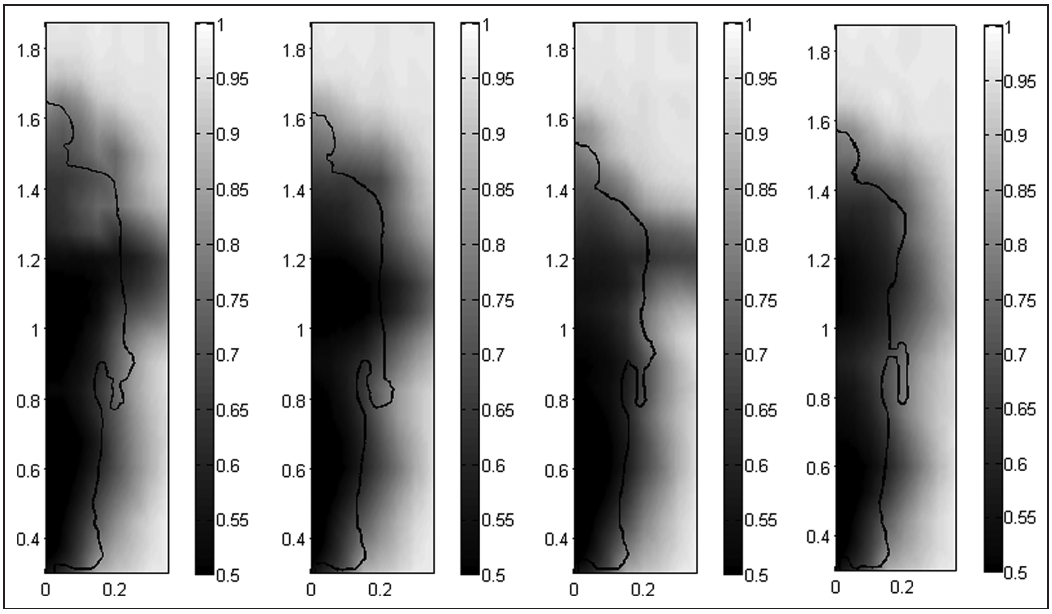

Figure 5. Normalised streamwise velocity in the wake of a cyclist: (L-R) Postures 1, 2, 5 and 6 (see Table 1 and Figures 1 and 2). Half of wake shown with centreline at 0 on the x-axis.

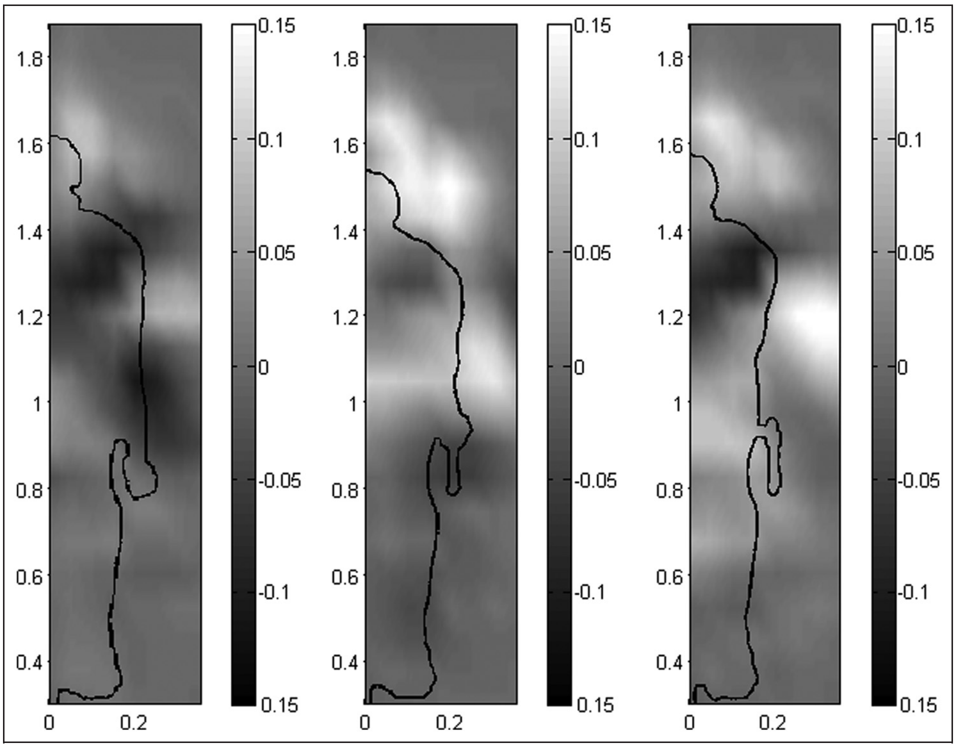

Figure 6. Streamwise velocity difference – streamwise velocity fields for Postures 2 (left), 5 (middle) and 6 (right), after subtracting the velocity field of Posture 1. Half of wake shown with centreline at 0 on the x-axis.

associated with the change in shoulder and arm position. Despite the differences in the wake velocity profile, the drag of Posture 2 is only 3.2% lower because the net velocity defect is similar. This result is important as it highlights that significant changes in the wake can occur from relatively subtle changes in posture.

Postures 5 and 6 have regions of higher velocity, particularly in the upper part of the wake, consistent with lowering the head and torso and reducing the frontal area. The profile for Posture 6 also has a very clear positive region on the outer edge of the profile at arm height. This is due to the aerobars bringing the arms inside the silhouette of the torso rather than

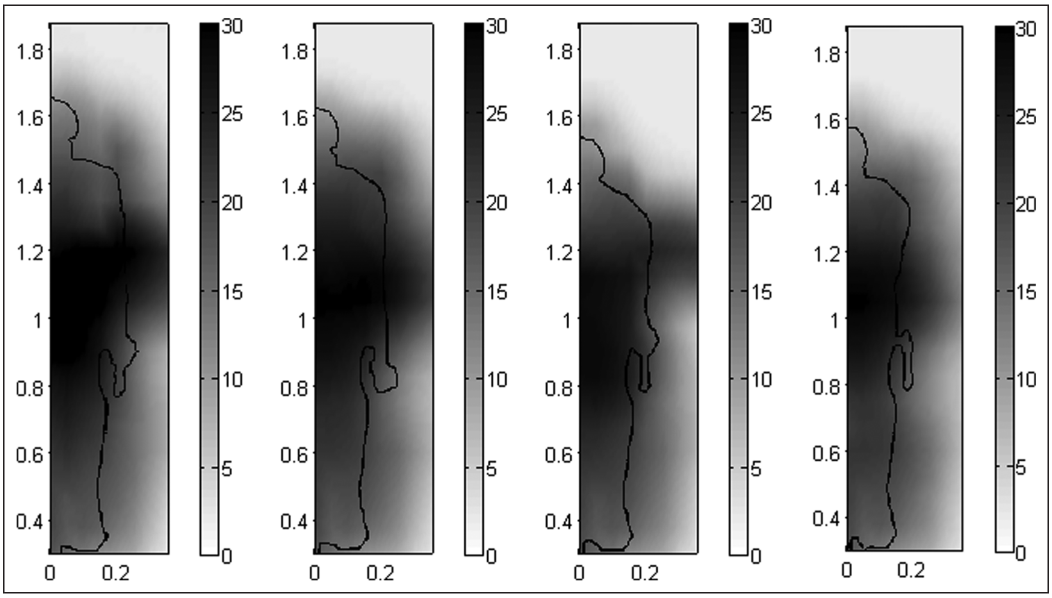

Figure 7. Turbulence intensity in the wake of a cyclist: (L-R) Postures 1, 2, 5 and 6 (see Table 1 and Figures 1 and 2). Half of wake shown with centreline at 0 on the x-axis.

sitting outside the line of the hips. This means that the wake of the upper arms partly shields the torso and the arm wake is not individually distinguishable downstream of the rider. In the road riding postures, the arms sit wide of the rider's hips, which leads to an additional contribution to the wake outside the line of the torso as seen for Postures 1, 2 and 5.

While Posture 5 has a slightly lower head and torso position than Posture 6, the wider arm position of Posture 5 contributes an additional velocity defect to the wake. As a result, the net drag for Posture 5 is higher than that for Posture 6. This highlights the importance of arm position to the drag of a cyclist. It follows that further drag reductions would be possible for Posture 5 by bringing the arms inside the torso silhouette and for Posture 6 by further lowering the rider height (although this may alter the nature of the postures).

Figure 7 shows the turbulence intensity ($Iuvw$) for each of the four postures and is a useful indicator for identifying regions of upstream separated flow. Turbulence levels can also be correlated with drag as it is associated with large viscous losses. For all cases, the highest turbulence levels are in the centre of the wake behind the lower torso and hips. This is consistent with the literature[24–26] as this is where the major separation region in the flow is contained. The lower drag cases (Postures 5 and 6) can be seen to have reduced turbulence in the upper region due to lower head and torso position. Posture 6 also shows lower turbulence levels at the edge of the frame at arm height. This is caused by the arms being inside the line of the torso, and so the wake of the arm impacts the front side of the torso leading to reduced area of turbulence in that region of the rider wake. Posture 5 shows a difference in this region with higher turbulence near the shoulder than hip. This is likely due to the forearm being horizontal such that only the upper arms present directly to the oncoming flow. It may also be that the presence of the forearm immediately upstream of the hip is disrupting the separation leading to the localised reduction in velocity defect and turbulence levels, compared even to Posture 6. These results confirm the relationship between cyclist geometry and flow topology observed in the streamwise velocity profiles (Figures 5 and 6).

These results highlight that the wake of a cyclist is highly turbulent and consistent with regions of large flow separation. In terms of optimisation, it can be concluded that lowering the head and torso will reduce the total area of velocity defect and turbulence intensity in the cyclist wake, as seen in Posture 5. In addition, Posture 5 reduced the frontal area of the arms by having the forearms horizontal. This reduced the contribution of the arms to the total wake area, thereby reducing the velocity defect and turbulence levels at the outer edges of the wake. The benefit of aerobars, even short draft-legal style bars, lies in the reduction of the arms from the rider silhouette. By bringing the arms inside the line of the hips, the area of velocity defect and high turbulence is narrowed as the wake of the arms impacts the rider torso and does not extend downstream past the hips. The lower velocity defect and reduced area of highly turbulent flow can be correlated with a drag reduction for the cyclist. This is consistent with the drag measurements, which showed Postures 5 and 6 to have 10%–16% lower drag than Postures 1 and 2.

Discussion

Existing literature on cycling posture

Several studies have previously investigated the effect of cyclist posture on aerodynamic drag, with various

Table 4. Summary of the literature for road cycling posture (wind speed in m/s).

	Posture	C_DA (m^2)	Technique	Dynamics	Wind speed	Blockage
Kyle and Burke[1]	Drops	0.32	Wind tunnel	Static	8.9–15.6	
	Crouch	0.26				
Zdravkovich et al.[8]	Hoods	0.26–0.38	Wind tunnel	Static	8.2	12.4%–16.2%
	Drops	0.23–0.34				
	Crouch	0.20–0.32				
Gibertini[7]	Drops	0.275–0.289	Wind tunnel	Dynamic	13.9	< 5%
Defraeye et al.[6]	Drops	0.243	Wind tunnel	Static	10 – 20	6%
Davies[19]	Drops	0.280	Wind tunnel	Dynamic	1.5–18.5	
Ménard et al.[25]	Drops	0.370	Wind tunnel			
Grappe et al.[2]	Drops	0.276	Constant power	Dynamic		
Pugh[20]	Crouch	0.33	Constant speed	Dynamic	< 8	
Capelli et al.[21]	Drops	0.251	Towed dynamometer	Dynamic	8.6–14.6	
Di Prampero et al.[22]	Drops	0.308	Towed dynamometer		5–16.5	
Gross et al.[23]	Drops	0.300–0.319	Coast down			
Kyle and Edelman[24]	Drops	0.272	Coast down			
This study	Hoods	0.343	Wind tunnel	Dynamic	12.5	< 9%
	Drops	0.332				
	Crouch	0.306				

postures being tested.[1,2,6–12] Primarily, these studies have looked at the advantages of time-trial postures over the standard road posture and the optimisation of time-trial performance. While few studies have investigated the relative performance of different riding postures on a conventional road bike, many studies have calculated the drag coefficient area (C_DA) of the conventional road racing posture. A summary of drag coefficients from the literature is provided in Table 4. The 'hoods', 'drops' and 'crouch' postures as described in the existing literature are represented by Postures 1-3, respectively, in this study.

It can be seen that there is considerable variation in the results of the literature for these three cycling postures. One of the key reasons for this is the dependence of drag on athlete geometry. Some results are the mean of multiple athletes; others are for single-athlete studies. It has been shown from tests with multiple athletes that individual body shape has a strong effect on drag.[8–11] For this reason, results in this study were also shown as a reduction from the reference state. This is intended to provide a more practical result in terms of expected fractional changes in performance for an arbitrary athlete.

Another cause of variability is the different methodologies and experimental setup used. In addition to direct force measurement from wind-tunnel measurements, various authors have conducted different types of on-road tests and have calculated drag from models. However, even within (the more controllable) wind-tunnel tests, there is a considerable spread in results. This will be contributed to by the procedure used. Note that some results are listed as static or dynamic. This refers to the state of the rider's legs. Some studies used a completely static athlete, while others examined full pedalling dynamics. It has been shown that the position of the legs has a strong effect on the flow field around a cyclist,[18–20] so it follows that dynamic force measurements will differ from static tests. This has been confirmed by wind-tunnel tests comparing the static and dynamic drag of the same athletes.[9] Although there is variation in the literature, the C_DA results from this investigation fit within accepted ranges for Postures 1-3.

Wake topology and drag force

It has been well established in the existing literature that the drag of a cyclist will vary with geometry and riding posture. The more difficult question lies in understanding why these force changes occur. Table 1 reports the frontal surface area for each of the nine test postures. This shows that there is a general correlation between drag and frontal surface area. As a general recommendation for cycling, adopting a posture that lowers frontal area will likely translate to reduced drag. This stems from the reduction in overall blockage, resulting in a smaller velocity defect and lower turbulence levels in the wake.

However, this trend is not universal, and frontal area alone does not fully explain changes in drag as there is significant variation in the drag coefficient with rider posture. Between the postures examined, the drag coefficient varies by 7.6% – the result of changes in the flow field. Wake surveys of sample postures (see Figures 4–6) showed that changes in streamwise velocity defect and turbulence intensity are evident with changes in riding posture. These can be correlated with reductions in drag as higher velocity in the wake indicates a smaller momentum loss across the body, and lower turbulence levels are indicative of reduced flow separation. Posture 5 had lower drag than the conventional postures (1 and 2) as a result of lowering the head and torso, which reduced the overall blockage and decreased the velocity defect in the upper region of the wake as well as the turbulence levels. The benefit of the aerobars for triathletes lies in the ability to bring the arms inside the line of the hips and torso. This reduces the frontal area, but also means that the wake of the arms impacts the torso, rather than extending downstream and combining with the wake of the torso. This was seen in the wake results for Posture 6 as reduced velocity defect and turbulence intensity in the area wide of the hips, where a contribution from the arms is visible for other postures.

Limitations of the power model

The power model assumes the athlete riding in the simplest flat road case and does not factor in interactions with other athletes, cornering, gradients or environmental wind conditions. From a practical perspective, it is acknowledged that technical aspects of a course may prohibit the use of certain postures. For example, cornering prohibits using aerobars (Postures 6–9) in favour of the greater control offered by a conventional drops grip (Posture 2 or 3). However, for most courses, there will still be straight sections of the course where such postures may be used and where these savings may be realised. Time savings are calculated assuming constant position for the duration of the race. As an indication, the proportion of the race spent in a given position can be applied to the indicated time saving with the same weighting. Environmental cross-wind conditions change the relative air vector to be at an angle to the rider. This not only affects an athlete's drag but also side force, roll moment and yaw moment. These loads have a complex effect on cycling dynamics and performance that is still not well understood and not examined here.

This study was conducted using the same equipment for all tests. This was done to isolate the effects of posture, independent of equipment selection. However, it is noted that certain postures, particularly eyes-lowered postures, may be influenced by helmet design, in the same way that time-trial postures benefit from a tear drop style helmet. Future studies should investigate the influence of helmet shape/selection on posture as it has been shown that there is a strong interaction between the flow over the head and the subsequent flow behaviour over the back.[24–26] As many components of the bicycle and athlete system interact, there are still many potential variables that could be explored. This investigation was designed to isolate the effect on relative performance of different body postures for a given cyclist and configuration.

Conclusion

Wind-tunnel experiments were conducted on a pedalling cyclist to investigate the effect of variations in body posture on aerodynamic drag and how this translates to performance. Similar effects have been observed in previous investigations but primarily for individual time-trial performance. This study specifically focussed on postures that are frequently used on a road bicycle, with the results showing that aerodynamic drag, and consequently performance, will vary substantially with riding posture. Nine body postures were selected as representative real-world postures used by elite cyclists and triathletes. In addition to direct drag measurements, a preliminary investigation into changes in the mean wake flow caused by changes in posture was conducted.

A maximum drag reduction of 17.4% was observed for a triathlete with draft-legal aerobars and with shoulders shrugged and 13.9% for a road cyclist when gripping the hoods with forearms horizontal, compared to the reference riding posture on the hoods (Posture 1). Using a simplified model for cycling power, these aerodynamic results were expressed as power saving. Due to the dominance of aerodynamic drag on required input power, the power saving expected from each posture is within 0.5% of the measured drag reduction. It was also found that the lowering of the rider's head resulted in increased drag (and power) compared to the same body position with eyes looking forward.

Wake surveys have confirmed that a cyclist is an aerodynamic bluff body, displaying large velocity defects and large areas of highly turbulent flow. It was seen that small changes in the body posture can significantly affect the wake distribution. However, it is possible to alter the wake without significantly affecting the net drag of the cyclist if regions are merely redistributed. Results showed that aerodynamic drag is associated with these regions of separated flow, and to minimise drag, it is important that all areas of the cyclist posture are optimised.

Lowering the head and torso was found to reduce the frontal area and translated to lower velocity defect and turbulence intensity in the wake. This in turn generally correlated with reduced drag for the cyclist. However, the position of the arms also has a significant impact on the wake topology and subsequently the aerodynamic drag. The use of aerobars to bring the arms inside the line of the hip reduced the width of the overall velocity defect and turbulence intensity. This correlated with force results which showed these postures to have generally lower drag than those postures with wide arms. As a recommendation for cyclist positioning, lowering the head and torso will generally translate to a reduction in aerodynamic drag by reducing the velocity defect and turbulence levels in the wake. However, to fully optimise aerodynamic performance, it is necessary to also bring the arms inside the silhouette of the torso and hips.

It is well established that aerodynamic drag is the dominant resistive force acting on elite-level cyclists and triathletes. Changes in cyclist posture have been shown to have a profound effect on the drag of a cyclist – the result of changes in the flow field. As such, utilising an optimised riding posture will deliver significant performance benefits to athletes in both road cycling and draft-legal triathlon.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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