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ORIGINAL ARTICLE

Aerodynamic drag interactions between cyclists in a team pursuit

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Abstract Performance in cycling events is strongly dependent on aerodynamic drag due to the high proportion of resistance that it contributes. The drag of individual cyclists has been shown to vary with riding posture and the drag of cyclists travelling in close proximity will vary as a function of separation distance. However, the influence of riding posture and the interplay between cyclists in a team is a complex problem that is not well understood. This study aims to develop a better understanding of the aerodynamic drag interactions between cyclists riding in a team as a function of their riding position. A team of four athletes was tested in the Monash University Wind Tunnel using a bespoke force balance that can measure drag on all four athletes simultaneously. Compared to an individual rider, the four riders in a team experienced mean drag savings of 5, 45, 55 and 57 % in positions 1, 2, 3 and 4 of the team, respectively. The results of individual athlete tests were shown to be a good indicator of drag response when applied in a team environment. Strong aerodynamic interactions were observed between the riders in a pursuit team. However, these varied significantly and appear to be unique functions of individual athlete body shape. Given the small winning margins at the elite level, a detailed understanding of the interactions between riders will deliver a performance edge. However, it appears necessary to test the actual athletes in situ to fully optimise performance as general trends were not consistent.

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1 Introduction

The understanding of aerodynamics in cycling is paramount due to the large proportion of resistance that drag contributes. It has been shown that over 90 % of a cyclist's resistance, at race speeds, is attributable to aerodynamic drag [1–3]. Consequently reductions in drag translate to improved performance.

In aerodynamic investigations of cycling, the drag of a cyclist is typically expressed as the drag coefficient area (C_DA), the product of the non-dimensional drag coefficient (C_D) and the frontal area (A). It is not typical to normalise by frontal area as it is a characteristic of each athlete that varies with body position. The drag coefficient area is defined as the drag force (D) normalised by the dynamic pressure ($\frac{1}{2}\rho V^2$); a function of forward speed relative to any wind component (V) and air density (ρ):

$$C_DA = \frac{D}{\frac{1}{2}\rho V^2} \qquad (1)$$

A reduction in a cyclist's drag coefficient area means that the cyclist will experience a lower drag force for a given dynamic pressure. Consequently, a higher speed can be achieved for the same output power.

A significant body of knowledge on cycling aerodynamics has been compiled over the past four decades. However, the majority of this work relates to individual cycling performance. This is despite the fact that road races are dominated by mass start events with cyclists riding in close proximity to one another, in addition to specific team events.

The study of fundamental bluff bodies and ground vehicles has shown that aerodynamic forces are strongly influenced by flow interactions between multiple bodies [4–8]. A review of literature on ground vehicle aerodynamic interactions revealed that drag is not only a function of the spatial distance between bodies, but is also dependent on the body geometry [9–11].

Given the high proportion of cycling resistance that is aerodynamic and the often small winning margins in elite competition, a detailed understanding of aerodynamic interactions between cyclists has the potential to deliver gains in numerous events. This has been previously recognised, with several authors investigating cycling specific interactions [12–18]. However, most studies have focussed on the influence of spatial separation between two cyclists and only examined the drag reduction benefit for the trailing rider. Furthermore, there have been a limited number of controlled wind tunnel experimental investigations, which allow for greater control over test parameters. This is largely due to the complex nature and large test section size required to test full-size athletes. For this reason, computational models have been seen as a more viable option particularly for studying geometric changes, as CFD is well suited to parametric optimisation studies. However, CFD is limited to static models as dynamic geometry simulations are currently too computationally expensive, especially for multiple riders.

The effect of body geometry in cycling aerodynamics has been previously investigated by numerous authors from the perspective of riding position (also termed posture) for single riders, but not in a team environment [1, 2, 12, 19–23]. Kyle [13] and Blocken et al. [15] compared the interaction effect for two riders in high and low riding positions as a function of separation distance. For these tests, both riders were in the same position with two separate data sets collected. At present, there remains a limited understanding of how rider geometry and posture influence aerodynamic interactions between team members. Edwards and Byrnes [24] investigated the variation in the magnitude of drag saving between different athletes by conducting constant speed runs with a group of 13 athletes. They found that the magnitude of the drafting effect varies considerably between athletes and suggested that drafting an athlete with a higher individual $C_D A$ would lead to a larger reduction in drag for the trailing rider.

This study aims to develop a better understanding of the aerodynamic drag interactions between cyclists riding in a team as a function of their riding position. This investigation will deliver performance gains in elite competition and also has the potential to provide insight into other bluff body interaction problems for complex geometries.

2 Methods

Four athletes were selected to act as a pursuit team, simulating the track event. The group comprised elite-level triathletes and cyclists. All were riding road specification time trial bicycles and wearing aerodynamic teardrop helmets. Athletes were using their own equipment and natural riding position, but with identical skin suits. The individuals ranged in size and body shape, which is representative of natural variation in team dynamics (see Table 1).

Testing was conducted in the Monash University Wind Tunnel with a nozzle area of 3 × 4 m and a test section length of 12 m. This nozzle area resulted in a blockage ratio of <5 % (ratio of body frontal area to nozzle cross section). Wind tunnel testing typically requires a blockage ratio less than 10 % to minimise flow distortion errors and ensure accurate force measurement. A bespoke rig was developed to measure the drag force of all four cyclists simultaneously. This allowed interplay between riders to be observed from the four drag measurements in each test run. The individual force balances utilised a single axis load cell aligned in the wind direction to measure drag with two sets of planar air bearings to isolate the axial force component (Fig. 1).

Bicycles were mounted to the rig by a pair of struts at the rear axle. The front wheel remained free, which enabled some lateral motion that was controlled by the athlete. This setup reduces interference from extra supporting structure at the front wheel and subsequent follow on effects downstream. The subtle movement also provides greater realism as it is more similar to on-road dynamics. Rollers under both wheels allowed pedalling and a belt connecting front and rear rollers drove the front wheel at the same speed as the rear. A fixed separation distance of 120 mm was maintained for all tests. This represents optimum positioning possible by elite pursuit teams.

A specific correction methodology was developed from the open jet corrections proposed by Mercker and Wiedemann [25] for automotive testing. Solid blockage and velocity perturbations were calculated modelling the four-rider team as a single test body as the streamline distortion is a product of the whole team volume. Therefore, the

Table 1 Dimensions of athlete participants including reference baseline $C_D A$ for athlete in solo test

	Height (m)	Mass (kg)	Baseline $C_D A$ (m^2)
Rider A	1.93	78	0.251
Rider B	1.83	78	0.224
Rider C	1.83	70	0.225
Rider D	1.76	60	0.214

Fig. 1 Team formation on rig in wind tunnel test section (displaying Sequence 1 in descending size order)

freestream velocity is corrected to be the same for all riders. Horizontal buoyancy corrections were applied to each position individually to account for variation in static pressure along the length of the test section. These corrections were applied to all force measurements to correct for velocity perturbations and horizontal buoyancy on multiple tandem bodies. A static anthropomorphic cycling-specific mannequin was used to characterise the force response of each rig. This revealed an uncertainty within 0.4 % in the corrected drag measurements across the four locations. Each force balance was calibrated and showed a response within 0.4 % (0.0003 m^2) of the applied loads.

During athlete testing, the mean experimental uncertainty in C_DA for athlete tests was 0.6 % (0.0007 m^2) for a given test configuration. This is primarily due to human factors arising from athlete subjects and the complications in repeating and maintaining constant body position and posture. The above-stated uncertainty does not eliminate an athlete from being able to recreate the same body position in subsequent tests over the course of the long test programme. To maintain repeatability, images were recorded for each test configuration from a fixed perspective to allow the tracking of changes in position and detect any errors or shifts in body position between tests.

All tests were conducted at 18 m s^{-1} (65 km h^{-1}), which is the approximate steady-state speed of an elite men's pursuit team maintained after the initial acceleration phase. Cyclist drag has previously been seen to be a function of Reynolds number and the same was observed with the four-rider team in sample tests [26]. The single test velocity was selected based on practical application and is in the flattest region of the Reynolds number-drag curve.

Three generic riding postures were identified that could be applied to any cyclist. These were head raised, head lowered and tucked and elbows together. Each of these was referenced from athletes' existing riding posture which was the baseline case. An example of the positioning can be seen in Fig. 2 for one of the athletes. Whilst variation between athletes means that each posture will have a unique effect on drag, they represent a generalised physical change that provides practical insight into geometric changes due to body position. As an indication the chin was raised or lowered approximately 75 mm and elbows brought together from the baseline case where elbows were positioned at approximately hip width (of the order of 300 mm depending on the athlete).

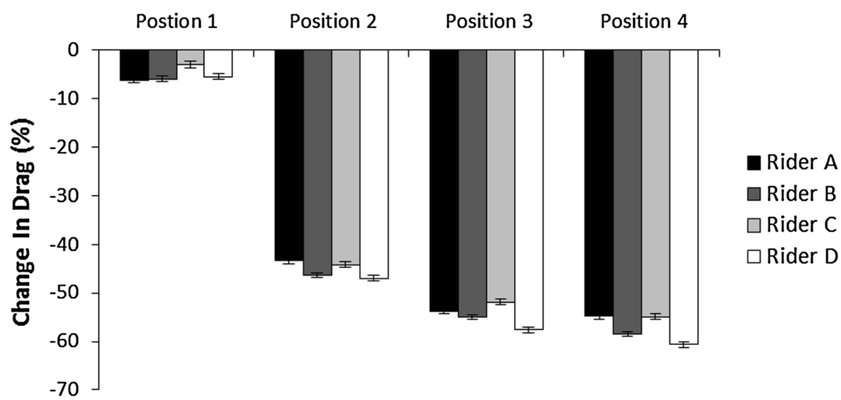
Tests were conducted with each individual rider consecutively adopting each position whilst the other athletes in the team remained in their baseline reference position. In addition, tests were conducted with the whole team in the same position. Only a single order of riders was tested, but all four possible sequences were tested so that each of the four riders occupied the lead position. This order was selected with the riders arranged in descending size order for the first sequence. In addition to team tests, reference tests were conducted for each rider individually in each of the four postures.

Riders were allowed to dictate their own cadence during tests, as this allowed them to maintain the most consistent body position and limit fatigue as well as ensuring that cadence was repeatable over the course of a long test program. All riders maintained a cadence in the range of 90–100 RPM through all tests and pedalling synchronisation was not monitored.

All testing reported in this article was conducted according to approval from the Monash University Human Research Ethics Committee. Project Number CF13/1326–2013000679.

Fig. 2 Body positions used during testing; (*L–R*) baseline, head raised, head lowered, elbows together

Fig. 3 Change in drag (%) at each position in a pursuit team compared to solo cyclist (*baseline* position only)



3 Results

3.1 Drag in a team pursuit

Drag measurements were recorded for each athlete at each position in the team for the four possible sequences. Each athlete's drag was also measured in isolation. This made it possible to determine the drag saving at each position in the team. The results can be seen in Fig. 3 which shows the drag reduction for each athlete. Results are for the baseline riding position only. Results from variation in body position are excluded from this set.

The mean drag reduction measured for riders in positions 1, 2, 3 and 4 of the team were 5, 45, 55 and 57 %, respectively. This is referenced to that athlete's drag as an isolated rider, rather than a percentage of leader power as this gives a better reference to change in performance. Total power saving (as a percentage) will always be less than drag reduction due to the friction force components in the equation of motion for cycling [27].

Whilst the drag reduction is broadly similar for each of the athletes, there are noticeable differences between them at each position in the team. This is consistent with the findings of Edwards and Byrnes [24]. This variation arises due to size and body shape differences between the athletes and the complex interactions that result. The flow field around a cyclist will be dominated by the general human form [30], but will have subtle variations due to differences between athletes such as limb length and diameter, torso shape, diameter and position, hip angle, muscle definition and size. When these are then combined with interaction effects within a team, it is unsurprising that the drag for each athlete differs at each position in the team. The mean deviation between the values of drag saving for each rider at each position was 1.6 %. In the scale of elite team pursuit racing, this change represents a significant margin. This variation between athletes suggests that specific team testing may be necessary to properly optimise performance of a pursuit team, rather than relying on general values.

Team pursuit aerodynamics has been previously investigated by Broker et al. [14] primarily using power data from track tests, but the study also reported on wind tunnel results. Defraeye et al. [16] also published results of a computational simulation of a four-rider pursuit team. Broker et al.'s results were all presented as a percentage of the lead rider's power output, as this is the form of data output from the track tests. Whilst this is not a precise indication of an individual's actual drag reduction, the results from the present study are presented in this format here for comparison (Fig. 4). The results presented are for

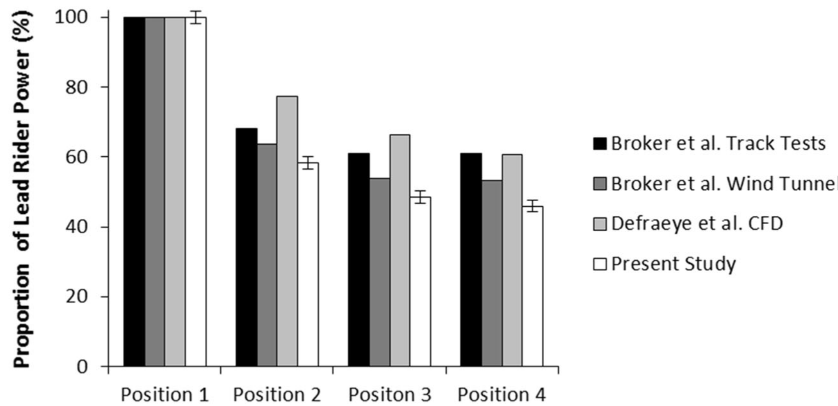


Fig. 4 Power required in a cycling team as percentage of leader comparison with Broker et al. [14] and Defraeye et al. [16]

the drag at each rider's baseline riding position. The drag measurements from the wind tunnel were expressed as power required (P) using a simplified equation of motion for cycling. Three sources of resistance are modelled for the cyclist: rolling resistance ($\mu[m_1 + m_2]g$), bearing resistance (F_B) and aerodynamic drag (D):

$$P = [\mu(m_1 + m_2)g + F_B + D]V. \tag{2}$$

This is a simplified form of the model derived by Martin et al. [27], assuming constant speed, zero gradient and no environmental wind (values for rolling resistance taken from Kyle and Burke [1] and Kyle [28] and bearing resistance from Wilson [29]). The C_DA results from Defraeye et al. were converted in an identical manner. The assumptions used in the model are shown in Table 2.

Comparing the four data sets, the track tests of Broker et al. are higher than those of the wind tunnel experiments. This was expected as the track tests have less control over relative spatial position and it has been previously seen for bluff bodies and cyclists that tandem drag is a strong function of proximity [12, 13, 15]. Due to variation in positioning during track tests, the drag for the trailing rider will increase and thus the measured power will be higher. Whilst this may represent a more practical performance guide, it is not an accurate method for determining drag interactions. The differences between wind tunnel studies may be due to variations in athlete geometry or methodology. Broker et al. provide very limited details of their experimental procedure for the wind tunnel data; hence corrections, setup, equipment selection and leg dynamics could all have influenced the results. In addition, the details of the power model used to express the force measurements as physical power were not disclosed and could affect the final values. The computational results of Defraeye et al. are significantly higher than both wind tunnel and track results. Their model did not include bicycles, only suspended rider geometries. As a result, the reported C_DA values are significantly lower than experimental results for the full system. It is therefore likely that the experimental results more closely reflect the realistic drag of a pursuit team.

Table 2 Values used in power Eq. (2) to model changes in drag as cycling power required

Athlete mass	m_1	70 kg
Bicycle mass	m_2	6.8 kg
Coefficient of rolling resistance	μ	0.005
Bearing friction (per wheel)	F_B	0.2 N
Cyclist velocity	V	18 m/s

3.2 Influence of the team environment on individual rider drag

Changing the posture and body position of a cyclist will affect their aerodynamic drag. This has been investigated for an isolated cyclist extensively in both academia and athlete performance evaluations [1, 2, 12, 19–23]. However, when a rider is then placed in a team and subject to interactions with other riders, the same magnitude of shift in the drag force may not be observed.

Each rider was tested for the four body positions in single rider reference tests as well as the full range of team combinations. From this data it was possible to compare the change in drag (ΔC_DA) observed for a given body position for a solo rider test and at each position in a team. The team ΔC_DA is defined as the change in drag for a given rider in formation referenced to the drag of that athlete at the baseline position in the given sequence (with all cyclists in their baseline position). Therefore, two sets of ΔC_DA values are obtained. One from the single rider tests (for each athlete at each body position, relative to baseline; ΔC_DA_S) and the second from the equivalent body position change in the team formation, referenced to the baseline position drag in the team formation (ΔC_DA_T). The difference between these two values indicates the influence of interaction effects.

The difference between the $\Delta C_D A$ values for the team and solo tests was calculated for each configuration by subtracting the solo rider difference ($\Delta C_D A_S$) from the difference recorded in the team test ($\Delta C_D A_T$). For consistency, this is then presented as a percentage of each individual rider's solo baseline drag ($C_D A_B$). If referenced to the drag in situ then the proportions will be distorted given the much lower reference drag of riders in a trailing position compared to the leader. The percentage change in $\Delta C_D A$ (Λ) was calculated for each rider, at each body position, in each team sequence:

$$\Lambda = \frac{\Delta C_D A_T - \Delta C_D A_S}{C_D A_B} \tag{3}$$

For the head raised position, which increased drag in all solo tests, a negative value of Λ indicates a smaller difference in the team testing (lower drag). For head tucked and elbows in, where drag generally decreased in solo tests, a negative indicates that the team difference ($\Delta C_D A_{Team}$) is greater than for solo tests (lower drag). As such, a negative value in all cases represents a beneficial result for that rider, as their drag is lower at that body position relative to what it would be if tested in an isolated single rider situation. The results are presented in Fig. 5. For example, a value of negative 2 % indicates that the drag is 2 % lower in the team formation than in the solo rider tests (referenced to solo baseline drag).

Each column in Fig. 5 represents the mean of the four cyclists tested in each position to give an overview of the general effect, irrespective of individual rider characteristics or performance. The labels "Head Up", "Head Down and "Elbows In" refer to the single rider adopting the given position while the others remain in the baseline position. The "Team" labels refer to all four riders in the team adopting that position. For example; "Team Up" describes the case where all four athletes in the team adopted the "Head Up" posture. In all cases it is seen that the difference value is negative and thus beneficial to the athlete. This indicates that interactions within the team generally had a favourable influence (from a performance perspective) on the $\Delta C_D A$ observed for the riders. In other words, similar body position changes lead to better drag performance in the team, compared to solo.

To understand Fig. 5, consider first the four data points plotted in the first segment; "Head Up". Each of the series represents the average value of Λ (change in $\Delta C_D A$) from the four athletes in the stated position in the team. As such, the first point (Position 1) with a value of −0.1 % is the mean value of Λ for the four athletes when riding in position 1 (the lead position of the team) in the "Head Up" posture. Thus, the plotted value of Λ is averaged across the four sequences such that the mean is taken for each athlete at the same respective position with the four-rider team. The other three series in this segment refer to the equivalent case for the trailing positions 2–4.

The error bars shown in Fig. 5 are greater than the 0.6 % uncertainty stated for the measured drag of an athlete. This error is due to averaging the change in $\Delta C_D A$ across the four athletes at each position in the team. A mean variation of 1.6 % was observed in the values of Λ for the four cyclist subjects (each column in Fig. 5). This is due to variations in rider geometry and the subsequent influence on the interactions. Given the magnitude of the mean values (maximum of 4 %), this highlights just how sensitive cyclist drag is to individual rider geometry and the complex interactions that are present between cyclists in a team. Note that this variation translates to some values of change in $\Delta C_D A$ (Λ) being positive for individual athlete cases. Figure 5 presents the mean values across all four athletes.

Whilst some of the results are small, many still represent significant changes in the drag of the athletes. For example, in the solo rider tests the drag of subjects B and D did not change significantly with elbow position. So whilst the

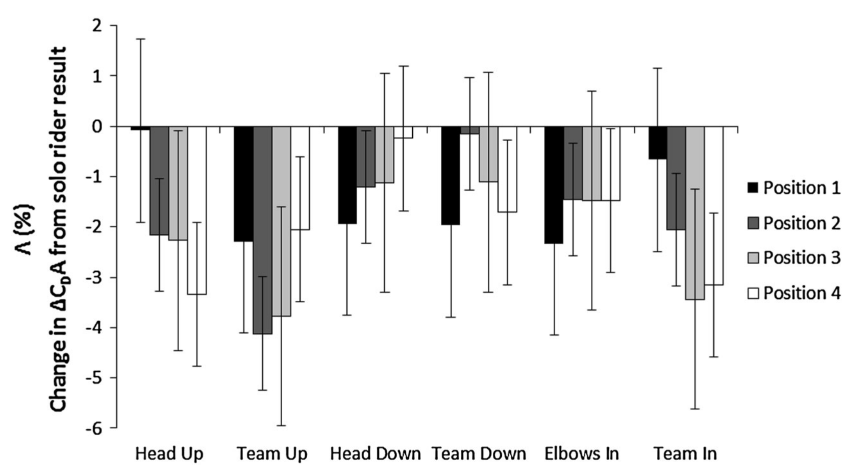


Fig. 5 Change in $\Delta C_D A$ (Λ) from solo to team as percentage of rider solo baseline drag. See Eq. 3

Table 3 Percentage change in drag from solo rider tests at each body position for each athlete referenced to the baseline position

	Rider A (%)	Rider B (%)	Rider C (%)	Rider D (%)
Head raised	6.7	5.9	9.3	6.0
Head down	−5.0	−1.5	−0.2	−1.5
Elbows together	−2.4	0.1	2.1	−0.4

result of −1.5 % for elbows in is relatively small, it represents a distinct interaction effect. As a reference, the change in drag from the solo rider tests is given in Table 3.

It is important to make the distinction that a value of 0 % in Fig. 5 indicates that the change in drag for that rider in the team test is equal to that seen in solo tests, not that the rider's drag is unchanged. It can, therefore, be stated that a change in drag observed from isolated single rider tests will likely translate to a team environment. That is to say that a posture that increases drag for a solo rider test will have the same effect in a team, though the magnitude of that increase will likely be smaller. Similarly, a posture that decreases drag in solo rider tests is likely to have the same effect when riding in a team, but with a greater drag reduction. These results are consistent despite the large variations between athletes exhibited by the size of the error bars.

3.3 Drag interplay between riders in a team pursuit

Riding in a team has been shown to change the magnitude of drag shift induced by body position changes for an individual rider. In addition to influencing their own drag, changing body position of a rider will also influence the flow around the other athletes in the team due to interaction effects and thus the drag of their teammates.

The simultaneous drag measurements of all four athletes allowed interference effects between the riders to be tracked. It was seen that under certain conditions, changing the body position of one rider could influence the drag of another team member. Results showed that there were significant interactions occurring between members of the team; however, few common trends were identified from the results (see Table 4). This is due to the complex nature of the flow interactions between the individuals due to subtle differences in athlete body shape.

One common result observed was that each time the lead rider lowered his head, the drag of the rider immediately behind increased. This was as expected, given that the trailing rider becomes more exposed to the oncoming flow. However, this trend does not directly translate to other positions in the team. For example, with the athlete in Position 2 adopting the head down posture, the drag of the rider in Position 3 does not necessarily increase. In fact, there were cases of both the rider behind and ahead being influenced and both positive and negative drag changes occurring.

Edwards and Byrnes [22] showed that a cyclist will experience a greater drag reduction if drafting from a rider with a higher C_DA. In this study it was hypothesised that a rider raising the head, thus increasing drag, would induce a greater drag reduction for the rider(s) downstream. However, this effect was not universally seen. In certain cases, the drag of riders further downstream was seen to increase and sometimes even had an upstream effect when applied to one of the trailing riders. Edwards and Byrnes were conducting road tests which have far less control over the spatial positioning of the riders than wind tunnel tests and this has been shown to have a large influence on drag. Their test method could have compromised on the accuracy with which sensitive variations in drag can be measured. In addition, the more complex case of interactions between four riders may have introduced additional effects.

In addition to a single rider changing body position, tests were also run with all four cyclists adopting the same posture. In this case, it was observed that the final rider always experienced a greater shift than when the three lead riders were in the baseline position. This applied to all three postures tested.

It is clear that there are drag interactions at play in a four-rider team, but riders are highly coupled by mechanisms more intricate than basic geometry and position identified here. A comprehensive understanding of these interactions could lead to performance benefits in competition. However, the differences between athletes' body position, riding style and geometry mean that without direct testing of the intended subjects these trends will be very difficult to predict. There can be little doubt that drag interactions between cyclists are very much athlete specific.

The stated repeatability of 0.6 % applies to back-to-back tests. However, subjects can still vary their position between different configurations. Image tracking revealed that Rider C had a slightly higher head position above baseline for Head 2–4 positions in Table 4. This has contributed to a higher drag and is not due to a strong forward interference effect from downstream.

3.4 Statistical correlation of drag interaction between riders

To test the inter-dependence of the drag of the riders, correlation coefficients were calculated using the corrected C_DA values for each sequence (see Fig. 6). The correlation coefficient ($r_{x,y}$) is defined as the sample covariance (between two samples, in this case the drag of two of the

Table 4 Percentage change in drag for each rider (change in C_DA in m^2), at each position in each sequence, referenced to baseline position in a given sequence (not as standalone rider)

	Sequence 1				Sequence 2				Sequence 3				Sequence 4			
	A	B	C	D	B	C	D	A	C	D	A	B	D	A	B	C
Head up 1	4.72	−5.42	0.58	3.23	8.97	−0.44	1.16	4.87	7.49	0.35	3.73	0.79	7.93	2.64	2.98	2.81
	(0.011)	(−0.007)	(0.001)	(0.003)	(0.019)	(−0.001)	(0.001)	(0.006)	(0.016)	(0.000)	(0.004)	(0.001)	(0.016)	(0.004)	(0.003)	(0.003)
Head up 2	−1.04	9.40	0.29	3.89	−0.18	10.18	−0.02	2.41	3.27	5.50	4.15	0.58	0.21	10.01	0.60	3.18
	(−0.002)	(0.011)	(0.000)	(0.003)	(0.000)	(0.013)	(0.000)	(0.003)	(0.007)	(0.006)	(0.005)	(0.001)	(0.000)	(0.014)	(0.001)	(0.003)
Head up 3	0.26	0.53	10.28	2.87	0.54	1.31	4.79	0.96	3.39	−2.35	9.94	−1.07	0.27	1.73	16.30	5.31
	(0.001)	(0.001)	(0.011)	(0.002)	(0.001)	(0.002)	(0.004)	(0.001)	(0.007)	(−0.003)	(0.012)	(−0.001)	(0.001)	(0.002)	(0.016)	(0.005)
Head up 4	0.94	0.35	2.94	8.12	−0.08	−0.88	−2.45	3.37	4.76	0.19	1.61	11.77	−1.20	2.93	2.08	11.07
	(0.002)	(0.000)	(0.003)	(0.007)	(0.000)	(−0.001)	(−0.002)	(0.004)	(0.010)	(0.000)	(0.002)	(0.011)	(−0.002)	(0.004)	(0.002)	(0.011)
Team up	5.80	3.21	8.09	12.20	4.63	7.02	0.18	7.07	5.81	2.22	10.20	12.36	1.84	8.27	9.32	14.79
	(0.014)	(0.004)	(0.009)	(0.010)	(0.010)	(0.009)	(0.000)	(0.008)	(0.013)	(0.003)	(0.012)	(0.012)	(0.004)	(0.012)	(0.009)	(0.015)
Head down 1	−4.91	1.45	1.30	−0.82	−3.21	3.12	0.46	−1.67	−6.43	2.51	0.25	−1.23	−2.18	2.36	0.80	0.29
	(−0.012)	(0.002)	(0.001)	(−0.001)	(−0.007)	(0.004)	(0.000)	(−0.002)	(−0.014)	(0.003)	(0.000)	(−0.001)	(−0.004)	(0.003)	(0.001)	(0.000)
Head down 2	0.07	−5.77	0.15	1.30	0.00	−5.44	−1.84	−3.02	−2.53	−5.93	−0.65	−0.64	−1.22	−6.55	5.63	−2.05
	(0.000)	(−0.007)	(0.000)	(0.001)	(0.000)	(−0.007)	(−0.002)	(−0.003)	(−0.006)	(−0.007)	(−0.001)	(−0.001)	(−0.002)	(−0.009)	(0.006)	(−0.002)
Head down 3	0.39	−1.54	−9.01	1.51	−0.03	−1.84	−5.91	−1.20	−1.22	1.70	−5.47	−0.57	−0.92	1.50	−7.33	0.43
	(0.001)	(−0.002)	(−0.010)	(0.001)	(0.000)	(−0.002)	(−0.005)	(−0.001)	(−0.003)	(0.002)	(−0.006)	(−0.001)	(−0.002)	(0.002)	(−0.007)	(0.000)
Head down 4	0.25	0.16	−0.11	−4.01	0.55	−2.44	−4.05	−5.82	1.51	−0.88	0.92	−6.75	−0.31	1.59	0.70	−4.72
	(0.001)	(0.000)	(0.000)	(−0.003)	(0.001)	(−0.003)	(−0.004)	(−0.007)	(0.003)	(−0.001)	(0.001)	(−0.006)	(−0.001)	(0.002)	(0.001)	(−0.005)
Team down	−5.63	−2.12	−10.53	−4.92	−2.29	−3.98	−4.12	−8.96	−6.60	−1.97	−6.51	−9.41	−2.30	−7.69	−6.20	−11.37
	(−0.013)	(−0.003)	(−0.011)	(−0.004)	(−0.005)	(−0.005)	(−0.004)	(−0.010)	(−0.014)	(−0.002)	(−0.008)	(−0.009)	(−0.005)	(−0.011)	(−0.006)	(−0.012)
Elbows in 1	−3.59	−3.40	−4.89	−1.06	−0.83	−1.16	−0.59	−2.04	−4.61	−1.41	−4.29	−3.40	−1.38	1.36	0.79	0.12
	(−0.008)	(−0.004)	(−0.005)	(−0.001)	(−0.002)	(−0.001)	(−0.001)	(−0.002)	(−0.010)	(−0.002)	(−0.005)	(−0.003)	(−0.003)	(0.002)	(0.001)	(0.000)
Elbows in 2	−0.61	−3.24	−1.68	4.05	1.56	−2.23	−0.31	−2.12	−0.62	−2.58	0.78	−0.70	0.73	−3.67	−1.02	−1.87
	(−0.001)	(−0.004)	(−0.002)	(0.003)	(0.003)	(−0.003)	(0.000)	(−0.002)	(−0.001)	(−0.003)	(0.001)	(−0.001)	(0.001)	(−0.005)	(−0.001)	(−0.002)
Elbows in 3	0.37	−0.92	−8.73	−2.50	2.15	−1.37	−5.67	−0.12	0.38	1.74	−0.60	−2.02	−0.24	−2.17	0.79	−2.60
	(0.001)	(−0.001)	(−0.009)	(−0.002)	(0.005)	(−0.002)	(−0.005)	(0.000)	(0.001)	(0.002)	(−0.001)	(−0.002)	(0.000)	(−0.003)	(0.001)	(−0.003)
Elbows in 4	0.13	−1.03	−4.62	−3.43	1.56	−1.30	−0.57	−6.27	1.51	−0.60	−0.72	−4.04	0.02	−1.10	0.40	−1.56
	(0.000)	(−0.001)	(−0.005)	(−0.003)	(0.003)	(−0.002)	(−0.001)	(−0.007)	(0.003)	(−0.001)	(−0.001)	(−0.004)	(0.000)	(−0.002)	(0.000)	(−0.002)
Team in	−2.58	−3.46	−14.26	−5.41	1.87	−4.16	−5.61	−9.43	−1.53	−3.17	−4.25	−4.30	−1.21	−5.21	−7.04	−11.22
	(−0.006)	(−0.004)	(−0.015)	(−0.005)	(0.004)	(−0.005)	(−0.005)	(−0.011)	(−0.003)	(−0.004)	(−0.005)	(−0.004)	(−0.002)	(−0.007)	(−0.007)	(−0.011)

"Team" rows describe results when all four riders adopted the same position. All other tests indicate one athlete out of the four at a given position whilst others remained in their baseline position, e.g. Head Up 1 refers to the first rider in that sequence raising the head whilst all other riders remained in their baseline position

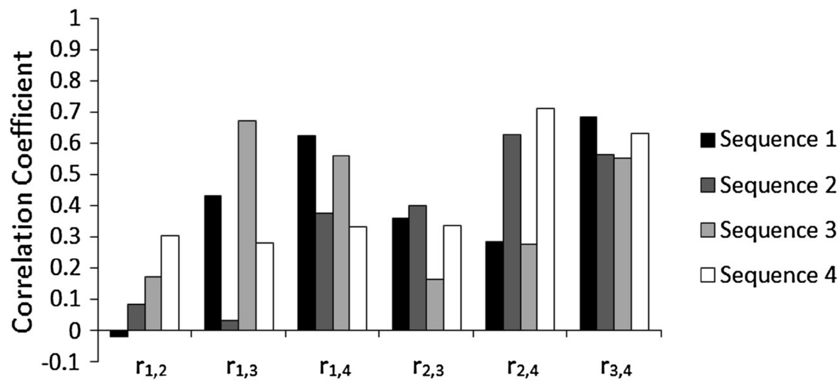


Fig. 6 Correlation coefficient for the drag between each position in the four cyclist team ($r_{1,2}$ = correlation coefficient between positions 1 and 2 in the rider pursuit team)

riders—s_{xy}) normalised by the product of the standard deviation for each of the two individual variables ($s_x s_y$):

$$r_{x,y} = \frac{s_{xy}}{s_x s_y} \tag{4}$$

Analysis was performed using the full data set, not mean values. Correlation was performed for all runs, using data for all body positions. Using the correlation coefficient allows the strength of interaction to be defined in a more quantitative manner. A strong correlation can be considered for values greater than 0.5 given the relatively high uncertainty imposed by human test subjects.

Considering the data by position in the team, irrespective of the athlete, it is seen that only positions 3 and 4 have a consistently high correlation. If the results are studied from an athlete perspective, ignoring the position in the file, riders A and C were seen to have a strong correlation for all sequences with others having mixed results depending on their position in the team.

This variation further shows the intricacy of the interplay between each of the cyclists in a four-rider team. It shows that drag of cyclist's in a team is linked, but the relationship is highly complex. It also confirms the concept of team-specific testing and the dependence of athlete geometry on the interaction effects. The variation of changes in drag seen across the results suggests that to properly optimise the aerodynamic interactions of an elite team requires in situ testing using specific athletes.

4 Discussion

When considering the aerodynamic interactions of a cycling team, it is important to consider how any new found knowledge can be utilised in the pursuit of performance. Contrary to perception, the sum drag of a team of cyclists (the sum of the drag for each of the four cyclists) is not the primary indicator of team performance in events such as track team pursuit or team sprint. Taking the team pursuit as an example, the team performance is measured by the finishing time, which is closely linked to the average speed that can be maintained over the 4,000 m event. There is also a transient component of the race where the riders are accelerating. During the steady-state phase the speed of the team is dictated by the leader, with each athlete sharing pace setting duties at the front. Since the leader is always exerting maximum power, speed will only increase by lowering the resistance; which is dominated by aerodynamic drag. As such, reducing the drag of the whole team by lowering the drag of the trailing three will not directly increase velocity. Obviously, there are physiological factors at play, such as recovery whilst trailing, which must be considered when translating aerodynamic knowledge into performance improvement. But the ideal situation, aerodynamically, would be to manipulate interactions such that drag of the lead rider is redistributed over the trailing three.

Such a situation was observed for certain test configurations; however, these reductions were small and were not seen for all test subjects. As such, it is clear that such an effect will be athlete specific. This is especially important given that negative interference effects were also seen where moving the rider in position 2 increased the lead riders drag. This highlights how sensitive interactions between cyclists can be and the importance of understanding these effects.

A more robust finding was that lowering the head and bringing elbows together generally resulted in lower drag for the lead rider. This corresponds with the results of solo tests where these changes had the same effect. In fact, the drag reduction in a team environment is generally greater than that observed in solo tests. Therefore, any change that can be made to lower an athlete's drag in individual tests will likely benefit the performance of the team, as it can be expected to lower their drag in the lead position.

Results show that it is possible for trailing riders to influence the drag of riders upstream. However, both positive and negative effects were observed, thus specific athlete testing appears necessary for aerodynamic optimisation. The drag response of athletes in a team is linked through complex mechanisms that extend beyond the basic postural changes investigated here. More detailed characterisation is needed to identify additional factors that can influence aerodynamic interactions within a team.

For elite performance, it is at this stage necessary to test desired athletes in a wind tunnel, as generalised performance trends could not be accurately modelled from the results of this study. In addition, it is possible that the pursuit of optimum team aerodynamics may lead to the dynamic positioning of cyclists; where each rider may adopt a different posture depending on the team's current sequence.

5 Conclusions

A team of four cyclists was tested in the wind tunnel and aerodynamic drag was measured simultaneously for each. Compared to an individual rider, the four riders in a team experienced mean drag savings of 5, 45, 55 and 57 % in positions 1, 2, 3 and 4 of the team, respectively.

Riding posture on the bicycle was varied to investigate the interaction effects as a function of geometry. Comparison with solo rider tests revealed that changes in drag observed in single rider tests for a given body position tend to translate to a team environment. However, the shift in the team scenario was generally more beneficial to that rider's performance. Postures that lowered drag had a greater decrease and postures that increased drag had a smaller change.

It was seen that there are strong aerodynamic interactions occurring between cyclists riding in a pursuit team. It is possible for a rider to influence the drag of team mates by changing his own riding posture. Interference effects were observed both upstream and downstream of a given rider. However, variability in the interaction effects highlights that cycling aerodynamic interactions are very much athlete specific and sensitive to individual geometry. The mechanisms controlling these interactions are more intricate than modelled in this study and require further investigation to understand and control within a team. The complexity of the interactions indicates the need for specific athlete testing for the optimisation of performance in elite teams and the potential for dynamic positioning within a team.

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Conflict of interest One of the authors of this paper is an employee of the AIS, a source of funding for this research. This does not represent a conflict of interest as it was a joint research project between the AIS and Monash University.

Ethics All testing reported in this article was conducted according to approval from the Monash University Human Research Ethics Committee. Project Number CF13/1326–2013000679.

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