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A quasi-static investigation of the effect of leg position on cyclist aerodynamic drag

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Abstract

The aerodynamic drag of a cyclist mannequin is measured in a ¾ open jet wind tunnel. The mannequin leg position is systematically varied over a complete crank cycle and aerodynamic drag measurements are taken every 15 degrees. The results show that rider aerodynamic drag is strongly affected by leg position with a difference between the maximum and minimum drag coefficients measured over a pedal cycle being approximately 15%. A small variation in cyclist frontal area is apparent over the pedal stroke, however the change in aerodynamic drag coefficient is identified as the dominant mechanism affecting cyclist drag. A series of flow visualization studies have been used to demonstrate the large effect that the position of the legs has on the flow around the entire body of the mannequin. It is observed that the flow regime is symmetrical for the low drag case and asymmetrical for the high drag case. This work highlights that the flow regime changes significantly throughout the pedal stroke of a cyclist, and consequently drag varies. This has implications in terms of analyzing cyclist aerodynamic performance as it highlights that multiple flow regimes should be considered.

Keywords: Cycling; aerodynamics drag; leg position; drag coefficient; flow regime

1. Introduction

Aerodynamics in speed orientated sports such as cycling has become one of the most important factors in improving the performance of cyclists. This is due to the fact that over 90% of the total resistive force

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acting on a cyclist at typical racing speeds is attributed to the aerodynamic drag component. Due to the size and bluff body nature of the cyclist geometry, the majority of this drag is a result of the pressure drag acting on the rider, which is a consequence of flow separation. Past investigations into the aerodynamic performance of riders have concluded that the most effective way to reduce this drag component is through a focus on a reduction in frontal surface area as shown by Kyle and Burke [1] in some of the first wind tunnel studies conducted on rider position. Cyclists currently riding at the limits to which they can reduce their frontal area and the strict UCI race-rules that further control rider position have limited the extent to which performance gains can be achieved through reductions in frontal surface area. This means that further investigations into cycling performance must look to new ways of reducing aerodynamic drag through targeting the drag coefficient.

In recent times the aerodynamic efficiency of cyclists has been improved through slight adjustments to position, helmet and bicycle component geometry and the use of zoned textured fabrics on skin suits such as that investigated by Kyle *et al* in the Nike Swift Spin project [2]. However many wind tunnel investigations into rider aerodynamics have reported that performance gains through use of such rider equipment is very sensitive to specific riders and their individual positions. This is because the effectiveness of a particular piece of equipment is determined by both the flow interactions with the equipment, and the way in which it integrates with the complex rider system. Unlike simple bluff body geometries, a rider consists of multiple body parts of complex curved shapes that vary significantly between individuals. Wind tunnel investigations into rider position by Zdravkovich [3] concluded that no single value of the drag coefficient can be specified for any one cycling position, a result of the strong dependence of the drag coefficient on the size and shape of the cyclist. For this reason, the most effective way to date to evaluate the aerodynamic performance of a cyclist has been through a trial and error approach to force measurement in a wind tunnel.

With further understanding of the local flow conditions around this complex system, the effect of changes to a cyclist's geometry and position on aerodynamic drag can be understood. Therefore the aerodynamic performance of a cyclist can be individually manipulated through equipment design targeted for specific flow conditions. Although there are numerous ways to manipulate the flow around a cyclist, the effect of leg position is of key importance due to the fact that all cyclists, in every discipline, must experience changes to their leg position around the crank.

In this quasi-steady analysis the effect of the position of the legs around the crank on both the drag of and flow around a cyclist are analyzed for static conditions. Further work on the role that cadence has on the aerodynamic forces and the evolution of the flow in the wake and around a cyclist is required. The effect cadence has on the aerodynamic forces of a cyclist is still not well understood. Although cadence is likely to impact the drag of a cyclist it is expected that the primary fluid mechanisms that determine drag will be similar for both static and pedaling conditions, due to the forward speed of a cyclist being significantly higher than the rotational speed of the legs around the crank even at high cadences. In investigating the aerodynamics of leg position, this work shows how a change in the flow regime around the cyclist has a dramatic impact on drag, highlighting the importance of considering multiple flow regimes when optimizing the aerodynamics of cyclists.

2. Experimental Investigations

Two wind tunnel studies have been used to investigate the effect of leg position on the aerodynamics of a full scale cyclist mannequin in a typical low drag time-trial position. The first involved drag measurements of static leg positions in 15° intervals around a complete crank cycle and the second involved flow visualizations at selected leg positions. Figure 1 shows the time-trial position, rider equipment and wind tunnel test set-up that was used for both the force and flow visualization investigations. The position of the legs is defined by the angle of the crank (θ) where the 0° crank position (shown in Figure 1) is when the crank is horizontal, with the right leg forward and the left leg back. The hip angle (Φ) of each leg is defined as the angle between the horizontal and the upper leg.

Both the force measurements and flow visualizations were conducted in the 3/4 open-jet test section of the large wind tunnel at the Department of Mechanical and Aerospace Engineering, Monash University. The blockage ratio of the mannequin in this test section based on the 2.6 x 4.0 m sectional area at the nozzle exit is approximately 4%. At the free-stream test speed of 16 m/s the turbulence intensity in the middle of the test section, where the mannequin was positioned, is less than 1.6%.

Fig. 1. Mannequin position/equipment and wind tunnel test-set up for both force and flow visualization studies

The mannequin ensures a high degree of repeatability of rider position and facilitates experimental studies not practical with a real rider. To ensure that force measurements and characteristic features of the wake are representative of a real cyclist, the mannequin was modelled on a typical male cyclist in a time-trial position. Knee, hip, shoulder, elbow and neck joints allow for the mannequin to be positioned in a wide range of representative cycling positions. The main geometric features of the mannequin include a standing height of 1.80 m, torso length of 650 mm, upper leg length of 450 mm, lower leg length 510 mm and a shoulder and hip width of 420 mm and 350 mm respectively.

Time averaged drag forces of static mannequin leg positions were measured using a six-component force balance of the piezoelectric Kistler type that was calibrated prior to force measurements. Struts attached to the either side of the front and rear wheel were used to rigidly fix the bicycle and mannequin system to the force balance, housed underneath the wind tunnel floor. The mannequin was positioned on a raised box with a cantilevered floor extending over the leading edge of the platform to limit the impact of the wind tunnel floor boundary layer on force results. Force measurements at each crank angle are taken as the mean result of three separate measurements sampled at 500 Hz for 30 seconds. Force measurements were shown to be very repeatable with a maximum standard deviation less than 0.5% of the mean drag at any given crank angle.

Both smoke and wool methods were used to visualize the near body and wake flow around the mannequin at a free-stream velocity of approximately 10m/s. Smoke was injected and the wool tufts were placed at various points around the body to highlight changes in flow conditions as leg position varied. These visualizations were simultaneously recorded on video footage from three cameras that were positioned from above, side and rear views.

3. Results

3.1. Force Measurements

Figure 2 shows the measured variation in drag area (CDA) determined at 15° increments in crank position for one complete crank cycle. The position of the legs around the crank has a large effect on the force, with a 20% variation in drag over both halves of the cycle, which is similar to that previously observed by Kyle et al [2]. The results for the two halves of the cycle agree well with each other, with a maximum variation in opposite leg positions of less than 5%. Both halves of the cycle show that the drag does not change significantly over the first 15° rotation of the crank when the upper thighs are in line (ΦLeft = ΦRight), and then increases rapidly until it reaches its maximum at the 75° and 255° crank positions. Following the peak in drag, in both halves of the cycle the drag decreases but at a reduced rate compared to that at which it increased. It can be seen that over the range of crank angles where the drag reduces that there is a more rapid reduction near the end of this range. The high repeatability of force measurements, along with flow visualization results to be discussed later, suggest that the difference in drag is a physical property of the mannequin possibly due to slight asymmetries in its geometry and position. These minor variations between opposite leg positions do not compromise the overall conclusions drawn, and we assume one half of the crank cycle to be representative of the data trend.

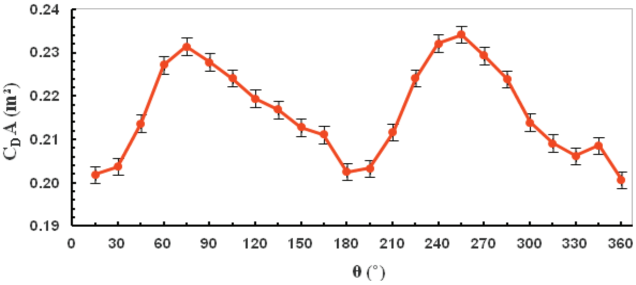

Fig. 2. Variation in drag area over a complete crank cycle

In an attempt to explain the large variation in drag with changes in leg position, the combined frontal surface area (FSA) of the mannequin and bicycle system was determined at each crank angle where force measurements were recorded. The frontal area was determined from photographs taken from 10 m in front of the mannequin, with a reference area held at the mid-point of the crank. Frontal area was then calculated by counting photograph pixels within the boundaries of the mannequin and the bicycle. Figure 3a shows that the variation in frontal area due to a change in leg position is less than 2% over a complete cycle of the crank. Although the frontal surface area maxima and minima coincide with the low and high drag crank positions, the small change in frontal area cannot account for the large variation in drag.

By taking into account the effect that changes in the total frontal area have on the drag and extracting them out of the drag area values, we obtain Figure 3b, which shows that the variations in drag are primarily due to the drag coefficient (C_D). The large change in the drag coefficient (up to 15%) suggests that as the legs are moved around the crank, there is a large change in the flow over the mannequin. Flow visualization studies show this to be the case and that the variation in drag with leg position is a result of a change in the flow regime and not frontal surface area.

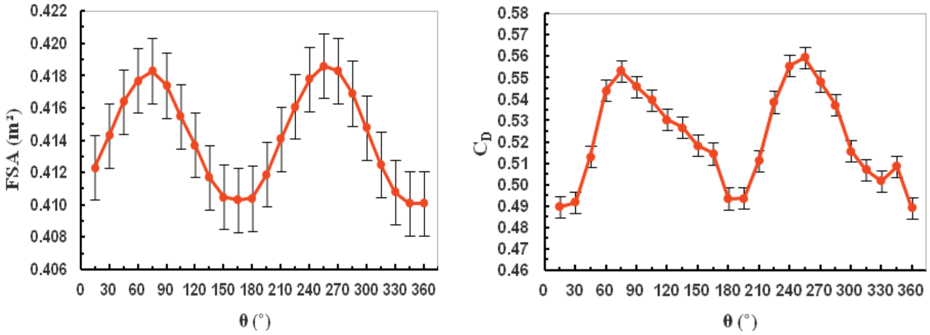

Fig. 3. (a) Variation in frontal area with crank angle; (b) Variation in the drag coefficient with crank angle

3.2. Flow Visualizations

To investigate the degree to which leg position effects the flow around the mannequin a series of flow visualization studies were performed with special emphasis placed on visualizations at low drag and high drag leg positions. The pressure drag which constitutes the majority of a cyclist's aerodynamic drag is dependent on where flow separates from the body which determines the size/shape of the wake. Flow visualizations show large variations in the flow over the body of the mannequin and in the near wake, highlighting the degree to which leg position effects the location at which flow separates from the entire body of the mannequin.

It is evident from smoke visualizations that multiple flow regimes exist throughout the course of the pedal stroke. Figure 4 shows still images of smoke injected into the flow just in front of the left and right hip for the 15° low drag leg position. Due to the flow being split evenly across both hips when the upper thighs are in-line the flow separates in a similar position on both hips. This results in the smoke particles taking an upwards trajectory into the wake from both sides of the body. The even separation of flow across the hips produces a wake that is characterized by a low drag symmetrical flow regime.

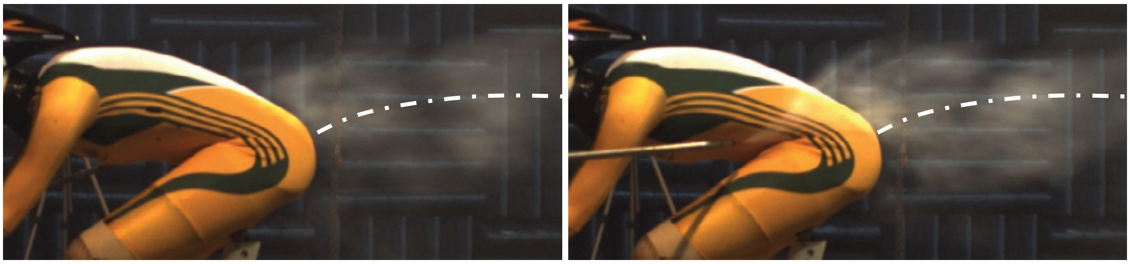

Fig. 4. Smoke injected over the left (a) and right (b) hips for θ = 15°

In contrast to this, smoke injected into the same regions for the high drag leg positions show a completely different asymmetrical flow regime. Figure 5a and 5b show side and rear views of smoke injected over the left and right hips for the 255° leg position respectively. Smoke injected on the left side of the body where the leg is in a down position follow an upwards trajectory into the wake showing the flow is largely separated over the left side of the torso and hip. Smoke injected on the right side of the body however follows a downwards path across the right hip into the wake showing that the flow remains attached over the hips were the leg is in an upwards position. Asymmetrical flow separation from the left and right sides of the body results in an asymmetrical flow regime in the near wake and over the whole bicycle/rider system.

Fig. 5. Smoke visualization showing asymmetry in flow separation over left (a) and right (b) hips for θ = 255°

The effect of leg position on the flow over the mannequin is further demonstrated with wool tuft flow visualizations pictured in Figure 6 showing the flow transitions from symmetrical to asymmetrical flow regimes over the entire torso as the position of the legs rotated around the crank. The long wool tuft attached to the tip of the helmet and running the length of the torso shows a symmetrical flow regime over the back resulting in the wool tuft running straight down the center of the back. For the high drag crank angles the tuft follows an "S" shaped pattern over the torso showing an asymmetrical flow regime over the back.

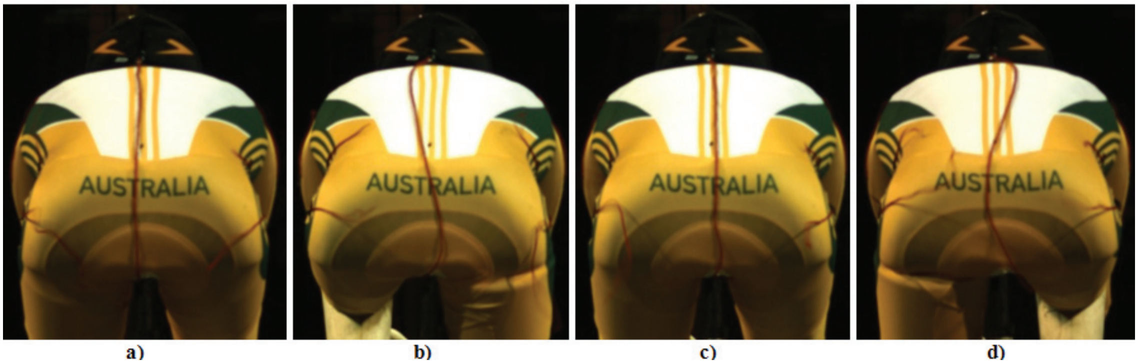

Fig. 6. Long wool tuft flow pattern over back for a) 15°; b) 75°; c) 195°; d) 255° leg positions

4. Conclusion

Two separate wind tunnel studies have demonstrated that the aerodynamics of a cyclist cannot be characterized by a single flow regime. Time averaged force measurements for a range of static leg positions revealed that the drag force varied significantly over the course of a complete crank revolution. The large variations in drag were primarily attributed to changes in the drag coefficient and not the small variations in frontal area throughout the course of the pedal stroke. This suggested a large change in the flow pattern around the entire cyclist/bicycle system which was demonstrated by flow visualizations using both smoke and wool tuft methods. Two separate symmetrical and asymmetrical flow regimes, which varied significantly from each other, were characterized for the low drag and high drag crank angles respectively. With the effectiveness of the design of rider equipment such as helmets, skin suits and the bicycle being very sensitive to the local flow conditions this work demonstrates that no singular flow regime can be considered when optimizing cyclist aerodynamics.

Acknowledgements

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