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A wind-tunnel case study: Increasing road cycling velocity by adopting an aerodynamically improved sprint position

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Abstract

The main aim of this study was to evaluate the potential to reduce the aerodynamic drag by studying road sprint cyclists' positions. A male and a female professional road cyclist participated in this wind-tunnel study. Aerodynamic drag measurements are presented for a total of five out-of-seat sprinting positions for each of the athletes under representative competition conditions. The largest reduction in aerodynamic drag measured for each athlete relative to their standard sprinting positions varied between 17% and 27%. The majority of this reduction in aerodynamic drag could be accounted for by changes in the athlete's projected frontal area. The largest variation in repeat drag coefficient area measurements of out-of-seat sprint positions was 5%, significantly higher than the typical $< 0.5\%$ observed for repeated testing of time-trial cycling positions. The majority of variation in repeated drag coefficient area measurements was attributed to reproducibility of position and sampling errors associated with time-averaged force measurements of large fluctuating forces.

Keywords

Aerodynamics, cycling, drag reduction, wind-tunnel methods, cycling position

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Introduction

Wind-tunnel testing has been used to assess the aerodynamic performance of cyclists since the mid-20th century.[1] Indeed, the vast majority of recent research has focused on time-trial positions.[2,3] This may be due to the specificity of time-trial races, in which cyclists compete individually over a set distance with the final ranking based on the course average speed.[4] In fact, during time trials, air resistance is by far the biggest resistance encountered by cyclists (i.e. $>90\%$ at 50 km/h).[5] Interestingly, the high average speed characterising time-trial competitions is relatively low when compared to the speed reached during road sprints, where peak velocities greater than 65 and 70 km/h have been reported in female and male professional cycling, respectively.[6,7] It is worth noting that road sprints are very common in road cycling, with at least one-third of competitions ending with a bunch sprint.[8] For the above-mentioned reasons, refining the aerodynamic characteristics of road sprinting positions has the potential to significantly improve cycling performances.

The *drag coefficient area* (CdA) is influenced by both the frontal surface area (FSA) and drag coefficient (Cd) of the cyclist.[9] This measure is directly proportional to the drag force at a fixed cycling speed. Reducing the FSA of a cyclist contributes to obtaining a diminution of the CdA.[9,10] Studies cited by Bassett et al.[11] have reported a weak correlation between CdA and FSA, with FSA accounting for approximately 50% of the variation in CdA between different riders and their riding positions, hence highlighting the importance of Cd. Previous research on the aerodynamics of cyclists has

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Figure 1. Road sprinter winning Stage 21 of the 2009 Tour de France (26 July 2009).
Source: Screenshot from https://youtu.be/4C4diLFBfcs?t=1m8s (visited on 15 July 2018).

provided good insight on what could contribute to optimal positioning. For example, reducing the torso angle of a cyclist generally reduces the CdA.[12,13] Some professional cyclists assume 'extreme' positions during road sprints, adopting a low torso angle and tucking their head (i.e. reducing FSA), likely with the aim to achieve a 'faster' sprinting position (see Figure 1).

One of the challenges with wind-tunnel testing of 'extreme' racing positions is the repeatability of the cyclist's position.[9] The validity of the wind-tunnel measurement process depends largely on the ability of the subject to maintain a stable and repeatable body position (i.e. upper body and head). For this reason, several studies have adopted the use of mannequins.[14–16] Assessing an actual out-of-the-saddle road cycling sprint position poses various methodological challenges, and to the best of the authors' knowledge an aerodynamic evaluation in a wind-tunnel setting has never been performed.

The main aim of this case study was to evaluate the potential to reduce the aerodynamic drag caused by road sprinters' positions by comparing different sprinting positions, including 'extreme' out-of-the-saddle positions. Using a repeated measures design, the second aim was to report the methodological challenges associated with measuring the aerodynamic drag coefficients of road cyclists riding in the out-of-the-saddle sprinting position.

Methods

A male (Subject 1) and female (Subject 2) professional road cyclist participated in this study. Written informed-consent documents were collected from each participant prior to wind-tunnel testing. All testing reported in this article was conducted according to approval from the Monash University Human Research Ethics Committee Project Number CF13/1326–2013000679. Each rider was tested in race-day cycling gear, which included their own road racing bicycle, helmet and apparel. Wind-tunnel testing of each athlete was performed in the 1.4-MW closed return-circuit open-jet wind tunnel at Monash University in Clayton, Australia. The wind tunnel has a jet exit of $2.6 \times 4.0\,m^2$ and a test section length of 11 m. The blockage ratio of the participants in the open-jet test section based on the jet-exit area is $< 3\%$. At wind-tunnel test speeds that were representative of the sprinting speeds achieved by each of the male (70 km/h) and female (60 km/h) athletes, the test section turbulence intensity was $\sim 1.6\%$. Figure 2 shows a schematic of the cyclists located in the open-jet test section. Key dimensions of the wind tunnel and the location of equipment within the tunnel are provided in Table 1.

A customised wind-tunnel force balance was used to measure the time-averaged aerodynamic drag force. A diagram of the force balance arrangement is depicted in Figure 3. The force balance consists of a floating table that sits on air-bearings. The air-bearing force balance system enables the axial force (drag) to be isolated and measured using a single component strain gauge.

The one-component strain gauge sensor (BCM Sensor model 1661) is a parallel bending beam 'single point' load cell rated at 50 kg with a 2.0-mV/V output. This sensor is connected to a load-cell amplifier that provides 10 V excitation to the load cell. At $100\times$ amplification, the outputs are 0–2 V over the load cells rated range. The output voltage from the load-cell amplifier is connected to the PC National Instruments DAQ system for scaling and data logging.

The bicycle is fixed to the air-bearing force balance table via struts that are attached to the front and rear wheel axles. Both front and rear wheels are positioned on top of rollers that are connected via a 1:1 belt drive that enable both front and rear wheels to rotate under pedalling conditions. To reduce the impact of the wind-tunnel floor boundary layer on the force measurements, the bicycle is positioned on a raised cantilevered platform that shields the force balance from the wind. Boundary-layer profile measurements showed that the height of the boundary layer at 500 mm from the leading edge of the front wheel was 56 mm. (This was the height above the floor at which $u/U_\infty = 0.99$.)

Prior to cycling testing, the force balance system consisting of the load cell and data acquisition system were calibrated over the relevant force range using dead weights of known masses. The calibration weights were suspended on a right angle moment arm that pivots on a 'knifes edge' and transfers the load to the force balance in the drag direction. The moment arm had a counter balance that could be adjusted so that there was negligible load on the force balance prior to the application of the calibration weights. For a steady load, the uncertainty associated with force measurements was $< 0.2\%$ of the applied load.

Force measurements of rider position were sampled at 250 Hz for 30 s. No attempt has been made to subtract the component of the aerodynamic force due to the struts on rider position force measurements. Each test involved recording baseline measurements for 10 s with the windspeed reduced to zero before and after

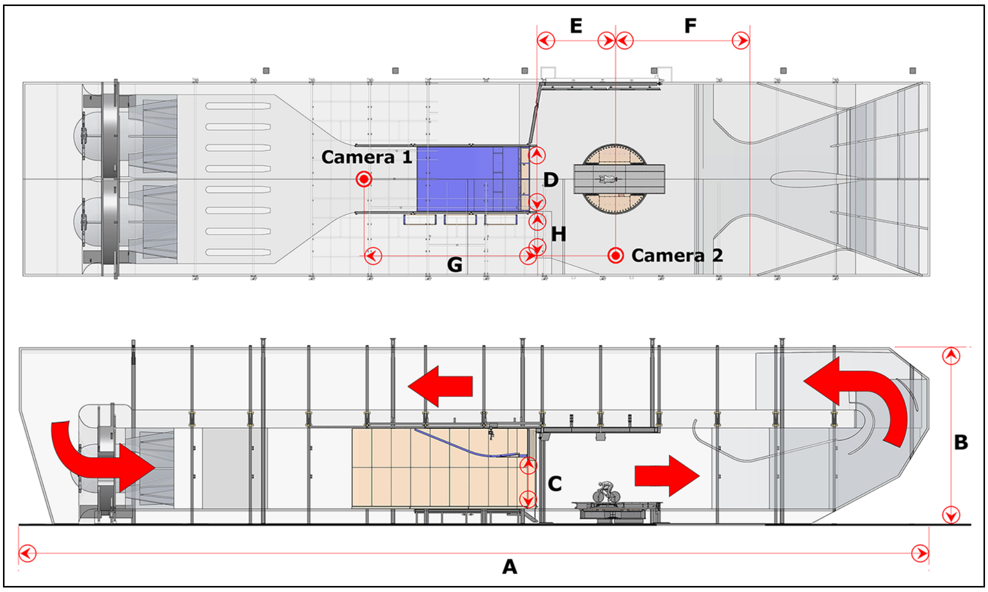

Figure 2. Monash wind-tunnel schematic (not to scale). Top and bottom images depict plan and profile views of the wind-tunnel circuit and test section, respectively.

Table 1. Key wind-tunnel dimensions and location of equipment.

Symbol	Name	Length (m)
A	Wind tunnel length	56.0
B	Wind tunnel height	11.0
C	Jet exit height	2.6
D	Jet exit width	4.0
E	Centre of test section from jet exit	4.7
F	Test section centre to collector	7.0
G	Upstream location of camera 1	12.2
H	Spanwise location of camera 2	4.9

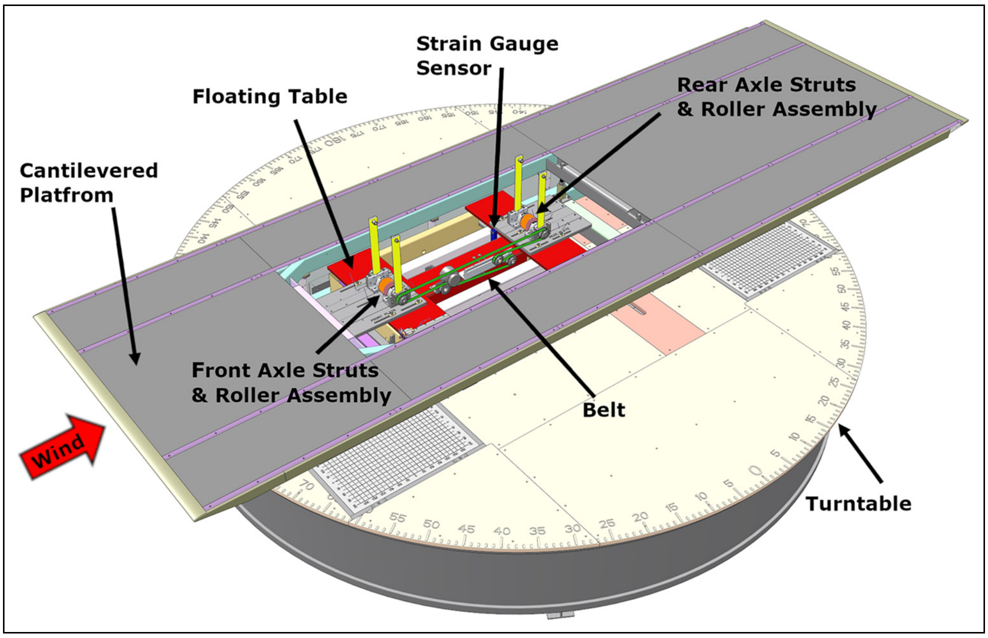

Figure 3. Diagram showing the primary force balance components.

taking force measurements for each rider position. This was done so that any drift in the force measurement system over the duration of a test could be monitored. In this case study, wind-tunnel force measurements are

Table 2. Subjects 1 and 2 road sprint positions wind-tunnel results.

Subject 1 male sprint position	No. of tests	ΔCdA (%)	ΔArea (%)	ΔCd (%)	RP ΔCdA (%)
1. Baseline	4	0.0	0.0	0.0	2.9
2. Low upper body, elbows in	3	−15.2	−19.0	4.7	5.0
3. Low and forward upper body, elbows in, head down	3	−26.6	−21.0	−7.1	3.6
4. Low upper body only	2	−5.2	−8.4	3.5	0.8
5. Low upper body, elbows in, head down	3	−16.5	−14.3	−2.5	3.8
Subject 2 female sprint position	**No. of tests**	**ΔCdA (%)**	**ΔArea (%)**	**ΔCd (%)**	**RP ΔCdA (%)**
1. Baseline	4	0.0	0.0	0.0	2.4
2. Low upper body, elbows in	2	−10.0	−10.3	0.3	0.4
3. Low and forward upper body, elbows in, head down	2	−16.6	−12.2	−5.1	0.1
4. Elbows in only	3	−7.7	−2.4	−5.4	1.7
5. Low upper body, elbows in (similar to 2)	3	−9.3	−9.9	0.7	1.8

CdA: drag coefficient area.
Athlete positions were designated by the changes made to the original baseline position (current racing position). Changes in athlete CdA, Area and Cd are relative to baseline position results. The repeat position (RP) ΔCdA represents the range of repeated CdA measurements recorded for each position as a percentage of the mean CdA value for each position.

presented for a total of five out-of-seat sprinting positions for each of the male and female athletes. The riders selected their own cadence throughout testing that enabled them to maintain a stable body position and limit fatigue throughout the course of the test day. Both riders maintained a cadence in the range of 70–90 r/min over the duration of the wind-tunnel testing.

Force measurements were repeated for each position. If the variation of the repeated CdA measurements between tests was $<1\%$, the next position was tested. If this condition was not satisfied, testing of that position continued until the variation in the mean CdA of repeated tests was $<1\%$. This test method applied to all positions tested, except the position that served as the baseline, which represented the athlete's current (standard) sprint position, for which a minimum of four repeated tests were performed. Force measurements were also performed without the athletes positioned on the bicycle (bike-only tests) at regular intervals throughout testing to assess the repeatability of the force measurements not associated with rider position that measured a large dynamic load. The variation in CdA of the bike-only measurements throughout the test day was $<0.0005\,m^2$.

Throughout wind-tunnel testing, the rider position was analysed from live-feed video footage of each test. Figure 2 shows the location of the Allied Vision Technologies GigE Cameras positioned around the wind-tunnel circuit to capture side-profile (sagittal plane) and frontal views. Projected frontal area has been estimated from still images acquired throughout testing from the upstream camera. This method is commonly used to measure the projected area of athletes and involves identifying the boundaries of the rider profile from images recorded from a frontal perspective.[10,17,18] Using a reference area that was positioned in line with the bicycle crank, the frontal area was estimated by counting pixels that lay within the boundaries of the bicycle and cyclist. As variation in the leg position around the crank cycle results in an ~2% variation in the projected frontal area,[14] only images for which the rider's legs were positioned within 5° of the horizontal crank position were selected for frontal-area analysis. In addition to the motion of the legs around the crank cycle, movement of the upper body during tests also contributes to variation in projected areas. For consistency only images that were representative of the mean rider position were selected for image analysis of frontal area (see the 'Discussion' section for further details).

Results

Changes in CdA (ΔCdA), Area (ΔArea) and Cd (ΔCd) relative to each athlete's starting baseline position are reported in Table 2. The maximum variation in CdA relative to baseline position was 27% for the male athlete. Also shown in Table 2 is the range of repeated CdA measurements (RP ΔCdA) for each position, which is represented as a percentage of the mean position CdA. RP ΔCdA varied between 0.1% and 5.0%, with Subject 1 tending to display more variability between trials of the same target sprinting position.

The ordering of position in Table 2 mirrors the sequence that was tested on the test day. The first three positions adopted in the wind tunnel were similar for both the subjects, while the last two positions differed (see Table 2 for details). Figure 4 shows an outline of each position tested from both frontal and side view perspectives. These have been overlaid for comparison.

These results provide important insight into the aerodynamic resistance of sprinters; however, there are factors that may affect the translation of these results into field scenarios. For example, the side-to-side movement of the bicycle and rider is not reproduced in the wind tunnel and this movement could exacerbate

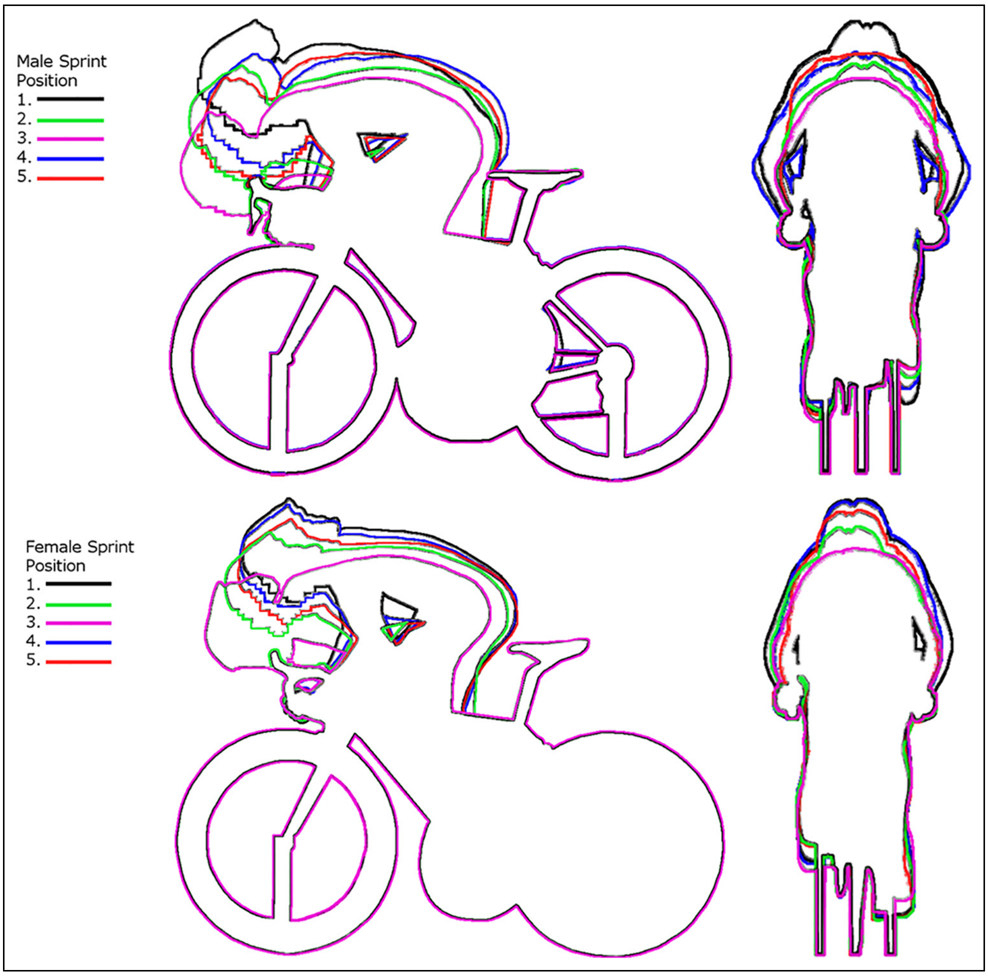

Figure 4. Overlays of male and female sprint position outlines from side and frontal view perspectives.

asymmetries in the wake. Furthermore, freestream turbulence conditions in the wind tunnel will differ from those experienced by cyclists out on the track or in the velodrome. The effects of freestream turbulence are known to induce transition to turbulent boundary layers sooner and increase mixing and spreading rate characteristics of turbulent wakes, both of which can have implications on the magnitude of aerodynamic forces.[19] The authors, therefore, hypothesise that while these differences in set-up and wind-tunnel flow conditions may have an effect on the overall drag coefficient, they will not necessarily change the relative findings presented here. Nonetheless, these certainly demand further study.

Discussion

Wind-tunnel drag area and projected frontal area measurements

The majority of the variation in CdA measured between changes made to baseline positions was a result of changes to the projected frontal area. The relationship between the change in FSA and CdA relative to the baseline positions is shown in Figure 5. Sprint positions in which the upper body was lowered and elbows positioned inwards (2) saw an average CdA reduction of ~13%, solely due to the FSA reduction. For these positions in which the head was in a more upright position (e.g. looking forward instead of at the front wheel), there was an average of 2.5% increase in Cd between the athletes, indicating that the upright head position was detrimental to aerodynamic efficiency.

In more ‘extreme’ positions, in which the upper body was lowered, elbows positioned inwards and the head in a downward position (3), reductions in aerodynamic drag were a result of both projected frontal area and the drag coefficient. Both male and female athletes saw reductions in Cd of ~6% and frontal area of ~16%. The largest reductions in both the projected frontal area and the drag coefficient for both the male and female athletes were observed in these ‘extreme’ racing positions, resulting in a mean ~22% (female and male range: 17%–27%) reduction in CdA.

Applying the cycling power model of Martin et al.[18] to these findings, it was possible to estimate the theoretical advantage of sprinting in the more aerodynamic positions (i.e. positions 2 and 3, with mean CdA

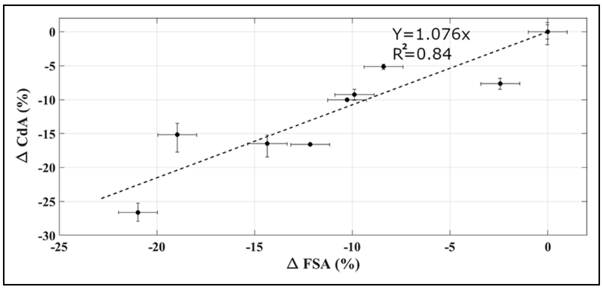

Figure 5. Variation in CdA measurements from baseline conditions of both male and female sprint positions as a function of percentage change in projected frontal area.

reductions of 12.6% and 21.6%, respectively), relative to the sprinters' original positions. In the sprints modelled below ideal conditions were assumed: a flat-road course, smooth asphalt, standard environmental conditions and no wind. In applying the power model to the male athlete, rider mass, mean power output and road sprint distance are representative of those detailed in published findings by Menaspà et al.[6] For the female athlete modelling, these reference values have been taken from findings reported on by Peiffer et al.[7]

A road male cyclist (~72 kg), sprinting over a 235-m distance and producing a mean power output of approximately 1020 W,[6] would reach the finish line 0.6 s earlier when adopting position 2 (12.6% reduction in CdA) and 0.9 s earlier with position 3 (21.6% reduction in CdA), when compared to sprinting in the baseline position 1. A road female cyclist (~64 kg), sprinting over a 325-m distance and producing a mean power output of approximately 680 W,[7] would reach the finish line 0.8 s earlier when adopting position 2 (12.6% reduction in CdA), and 1.3 s earlier with position 3 (21.6% reduction in CdA), when compared to the baseline position 1.

Further studies determining how pedalling in the more aerodynamic positions might affect sprint power outputs, and more importantly sprint velocity in the field, are warranted.

Reproducibility of sprint position CdA measurements

Compared to previous CdA measurements of seated cycling positions using a similar test methodology as outlined in Section C,[20] out-of-seat positions tested as part of this study showed a much larger variation in CdA between repeated tests. For each out-of-seat sprinting position, Table 2 provides the range of repeated CdA measurements as a percentage of the mean position CdA (RP ΔCdA). The largest variation in repeat CdA measurements of out-of-seat positions tested in this study was 0.01 m^2 or 5%. To put this into perspective from the authors' experience, the variation in repeated testing of professional time-trial cyclist positions is typically on the order of 0.001 m^2 or $< 0.5\%$ and the variation in repeated bike-only tests performed as part of this study throughout the entire test day was $< 0.0005\,m^2$.

There are many sources that contribute to the scatter of repeated time-averaged drag-area measurements of athlete position. These can broadly be grouped into precision and sampling errors associated with force balance and dynamic pressure measurements, change in ambient conditions, variability in athlete position and changes in flow phenomena between tests (e.g. variation in separation points due to Reynolds number effects and bi-stable wake-flow phenomena). In this case study, the authors focus on the effect of two sources that could account for the majority of the variation in repeated CdA measurements. These include (1) stability and reproducibility of position and (2) sampling errors associated with time-averaged force measurements of large fluctuating forces.

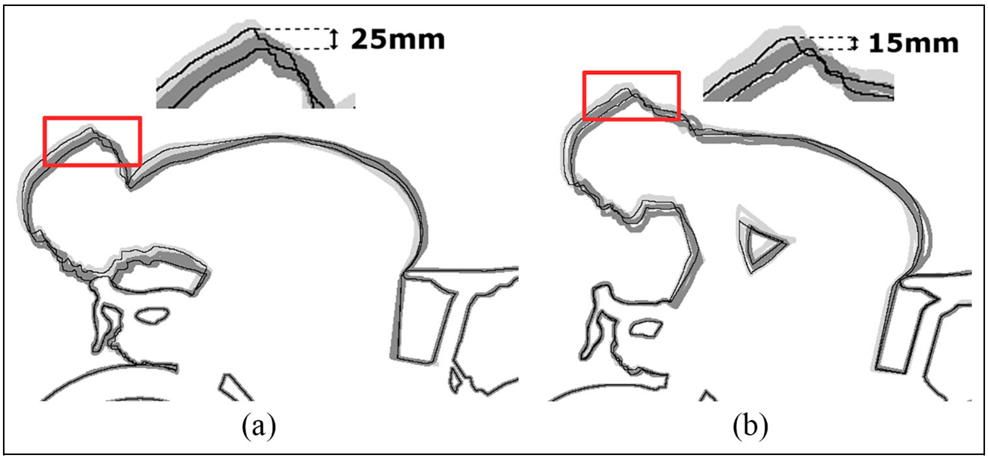

Figure 6. Image analysis results looking into the variation in position within and between repeated tests of: (a) male position 2 and (b) female baseline position. The black lines represent the mean position of each test. Light and dark grey lines show the variation of position within each test.

Through comparison of images of out-of-seat positions between repeated tests, it was evident that the level of difficulty in maintaining and replicating out-of-seat positions is increased compared to seated positions, such as those used by time-trial cyclists. This is a result of the increased range of motion of an athlete in an out-of-seat position and the difficulty in holding a steady position when the seat is no longer providing a reference point and supporting the majority of the athlete's weight.

Figure 6 highlights both the variation of position within a test and the ability of both athletes to replicate their positions between repeated tests. The figure depicts positions of the athletes where the largest variation in CdA between repeated tests was observed. The black lines represent the mean position and the grey lines represent the variation of position within each test. The maximum variation in CdA for the male athlete was 5% (position 2) and 2.4% for the female athlete (baseline position 1). Frontal area estimates of mean positions could not account for the variation in CdA between repeated tests. The variation in mean position FSA for both athletes between repeat position measurements was $<1\%$ and within the uncertainty associated with the measurement of FSA of pedalling athletes.

The image analysis technique depicted in Figure 6 was applied to all positions tested as part of this study. This analysis revealed that the mean head or chin height above the wind-tunnel floor was a very good indicator of the ranking of repeated CdA measurements of position from highest to lowest, with lower head positions and torso angles resulting in lower CdA measurements. For positions scrutinised in Figure 6, the variation of head height within a test was on the order of 30 mm for both male and female athletes and was typical for the other positions tested in this study. The mean head height between repeated tests varied between 10 and 30 mm across all positions tested. Smaller changes in the mean head height between repeated tests resulted in increased reproducibility of position CdA. Drawing on previous wind-tunnel research into cycling position

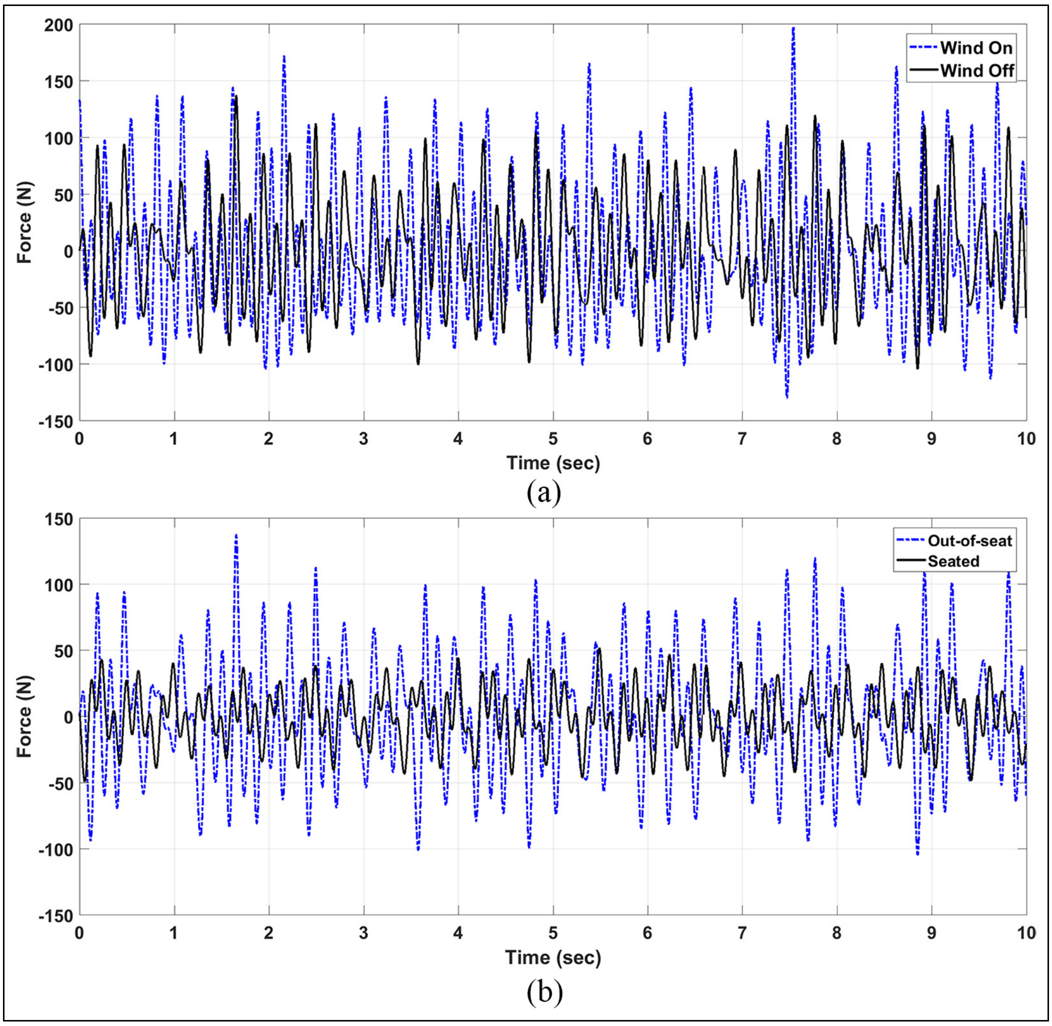

Figure 7. Force time series measured for (a) out-of-seat sprint position during wind on and off testing and (b) out-of-seat and seated position with the wind off. Note that the sample mean has been subtracted from each time series to enable an assessment of the fluctuating load.

performed by the authors, the upper body position of elite athletes holding seated positions is typically maintained within tests and reproduced to within ~10 mm.

In addition to the stability and reproducibility of rider position, sampling errors were also found to contribute to the increase in the variation of repeated CdA measurements of out-of-seat positions compared to seated ones. The sampling errors described herein are associated with the error in time-averaged measurements of periodic wave forms, which vary with ~A/N, where A is the signal amplitude and N is the number of periods over which the time-averaged measurement is made. The unsteady load component of pedalling cyclist force measurements is a result of cyclic inertial forces due to the pedalling motion of the legs and the back-and-forth rocking motion of the body; fluctuating aerodynamic loads as a result of unsteady separation points, turbulent free stream conditions and varying athlete position (legs and upper body motion); and the response characteristics of the force balance. Figure 7(a) compares the time series of force measurements sampled with the female sprint athlete pedalling with the wind switched on and off for the baseline out-of-seat position. The comparison enables the relative contribution of the unsteady load components to be assessed. It shows that there is a strong periodic frequency component associated with twice the pedalling cadence and that the periodic inertial loads account for the majority of the fluctuating component of aerodynamic force measurements of pedalling athletes.

Figure 7(b) compares the time series of force balance measurements recorded for seated and out-of-seat positions with the wind off. Time-averaged measurements of these time series are typical of those used to tare the force balance prior to aerodynamic force measurement and assess any drift in the force balance over the duration of aerodynamic force measurements. Compared to seated positions, there is a significant increase in the amplitude of the unsteady force signal for the out-of-seat positions. For this example, the ratio of the amplitude of the two time series is approximately 2. In order to achieve the same time-average sampling convergence uncertainty would mean that the out-of-seat position would require approximately twice the sampling period as the seated position. When testing more 'extreme aerodynamic positions', it is likely that the athlete will have no or very limited prior training in adopting these positions, and thus the ability to maintain repeatable extreme positions is unlikely. As a result, the choice of the length of the sampling period is a compromise between accuracy in time-averaged measurements or increased uncertainty in the ability to define athlete position throughout the test.

In addition to increasing the sampling period, this type of sampling error can be reduced by obtaining time-averaged force measurements of pedalling cyclists that only include whole numbers of pedal strokes. Through post-processing, this condition was enforced on the two wind-off measurements that were used to assess the drift over the duration of aerodynamic force measurements. By applying this condition through cropping a small number of samples from the averaging sample, it was found that this sampling error could account for approximately 60% of the measured drift. For tests where large drift measurements were observed, which were on the order of 1 N, this sampling error is on the order of 1% of the measured aerodynamic drag associated with athlete position. To put this into perspective, the drift associated with bike-only measurements with the athlete removed from the system was $< 0.1\%$ of the measured aerodynamic drag of both athletes involved in this study.

Conclusion

Adopting sprinting positions in which the upper body is lowered, elbows are positioned inwards and the head is in a downward position, saw reductions in aerodynamic drag that were due to both reduction of the projected frontal area and drag coefficient. The largest aerodynamic performance improvement for both the male and female athletes resulted in a mean 22% (range: 17%–27%) reduction of the CdA. This could generate a time advantage of approximately 1 s (0.9 and 1.3 s in men and women, respectively) over the duration of a typical (final-phase) road sprint.

The largest variation in repeat CdA measurements of out-of-seat sprint positions tested in this study was ~5%, significantly higher than the typical $< 0.5\%$ observed in repeated testing of professional (seated) time-trial cycling positions using the same methodology. The majority of the variation in repeated CdA measurements was due to: (1) stability and reproducibility of position and (2) sampling errors associated with time-averaged force measurements of large fluctuating forces. This indicates that the choice of the length of the sampling period should be considered carefully when testing positions that place athletes out of their comfort zones, taking into account the ability of the athlete to maintain position and the magnitude of the unsteady loads associated with pedalling.

Declaration of conflicting interests

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