The aerodynamic assessment of tandem cyclists in preparation for the 2021 Paralympic Games: A case study

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Abstract

Reducing the level of aerodynamic drag (CdA) via use of a wind tunnel will ultimately improve a competitive cyclists performance. Whilst this tool is widely considered a 'gold standard', previous studies have centered on single riders or scale models to evaluate aerodynamic drag. No study to date has assessed the precision of wind tunnel testing with the additional perceived complexity of a tandem bicycle with a pair of competitive paracyclists.

The first part of this investigation evaluated the use of a wind tunnel in the assessment of tandem paracyclists. A male and female team of paracyclists riding tandem versions of either a time trial track bicycle or a road/time trial bicycle undertook a series of measurement intervals in a wind tunnel. Three different combinations of these riders and bicycles obtained a Coefficient of Variation of their mean CdA of 1.8-2.6%.

The second part of this investigation acted as a case study by implementing a range of aerodynamic interventions to potentially reduce the male team's CdA. For example, progressive efforts reduced a team's CdA from the baseline of 0.338 m^2 to ultimately 0.321 m^2 predominately by lowering both tandem riders heads Whilst tandem cyclist performance enhancement has recieved scant attention in the past, this case study only highlights the value of doing so in the future.

Keywords

Tandem bicycle, paracycling, aerodynamic drag, cycling, paralympic games, wind tunnel testing, disability

Introduction

Aerodynamic drag represents approximately 94% of the total resistive force that acts on a single cyclist when moving at approximately 50 km/h.[1] Therefore, reduction of this resistance is essential to maximising the performance of elite athletes. One of the methods proposed to assess such resistant forces acting on cyclists is via the use of a wind tunnel.[1,2] The assessment of cyclists aerodynamic drag when using a wind tunnel has been undertaken extensively and been used to assess changes in riding position,[3] packs of cyclists when drafting,[1] the assessments of sprinting positions[4], changes in equipment[5] or to validate other methods such as velodrome testing[6] and outdoor road cycling mathematical models.[7] As a method when assessing cyclists, it has been considered as ‘the gold standard’ in aerodynamic measurement.[8]

However, while several studies have evaluated cyclists using such tools, there has been far less attention paid to cyclists with a disability[9] and only relatively recently with respect to tandems.[10] It is therefore premature to assume that paracyclists would exhibit the same behaviour as able-bodied athletes due to a lack of case studies and the potential variety, scale and assymetry that physical disability may provide. Few studies to date have begun to address the aerodynamic drag of tandem cyclists and those that have taken place are all mainly attributed to the same author mentioned above.[10-13] In the studies that have evaluated tandem cyclists ‘Coefficient of Aerodynamic Drag’ (CdA), scale models of cyclists were used.[10,11] This meant that the precision of such experiments when using actual cyclists riding and pedalling a tandem bicycle were both assumed and simplified, despite the likely added complexity of two riders pedalling in unison in reality. As a result, it would be of value to ascertain the precision of tandem cycling aerodynamic drag when measured in a wind tunnel. Furthermore, the reduction of paracyclists aerodynamic drag is key to maximising their performance at major sporting events like the Paralympic Games. Such studies are of use to help communicate ideas to athletes, coaches and practitioners to pursue in the future and to provide case studies to demonstrate their impact.

This paper will begin to address the lack of attention and limitations of the previous studies into tandem cycling by investigating the precision of aerodynamic drag measurement of live paracyclists. It will also perform a case study by assessing a range of positional and technological changes made to a male paracycling team ahead of the 2021 Paralympic Games that were held in Tokyo.

Methods

Wind tunnel design

A wind tunnel was used to evaluate the aerodynamic drag of tandem cycling teams. The wind tunnel was located at the Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Poland. This facility was a closed loop wind tunnel with a test section of 2 m in height and 2.5 m in width. The length of the test chamber was 10 m. The area of the cross section in the measurement area was 5.17 m^2. The blockage ratio was approximately 6.2-8.5% for all the tests that took place. The nominal turbulence intensity where the riders were positioned was 3.5%. The velocity profile in the test section was uniform except for any boundary layers produced on the walls surface. The reference velocity was measured through use of a Pitot-static tube mounted on the upper wall, positioned 300 mm from the walls surface.

For measuring the aerodynamic drag of cyclists, a platform of 2.5 m length was mounted below the floor for the measurement of the longitudinal force. This was shielded from the wind. This force balance platform had three cylindrical rollers to allow the cyclists to pedal and were connected by a belt to provide power transmission and to allow both wheels to rotate in unison. One roller supported the front wheel and two rollers supported the rear wheel. The rear wheel axle was then supported via a stabilising strut on each side to help stabilise the bicycle. The force balance was zeroed before each test.

Wind tunnel test protocol

The cyclists would be asked to pedal the tandem bicycle at a freely chosen cadence and once they arrived at relatively uniform exercise intensity, a measurement test run interval would then be conducted. Data was sampled at 10 kHz for a 90 s test period and mean values from this period are used in the analysis. The test air speed was set at 61.1 km/h (male teams) and 54.8 km/h (female teams). The rationale for these magnitudes and differences between the teams was due to them being defined as each tandem team's typical mean race velocity achieved during their individual pursuit track events. The yaw angle was 0 degrees. The length of the tandem and the size of the cross section of the wind tunnel prevented a greater range of yaw angles from being assessed.

After the experiment to ascertain the test methods precision was concluded, a range of aerodynamic interventions were then applied to the male tandem team. These interventions were always conceded to not produce universal findings, were deemed relative to the male tandem teams they were applied to and were intended in this paper to act solely as the basis of a case study. These interventions are summarised in Table 1.

[INSERT TABLE 1 HERE]

The rationale behind these interventions served to act to reduce the tandem teams overall CdA. In some other cases this rationale acted as a means to optimise existing equipment (e.g. handlebar positioning or head height) or to act as a compromise taken on balance against a hydration strategy (e.g. the impact of a bottle cage).

Participants

Two teams of elite-level tandem paracyclists participated in this study. ‘Elite level’ was defined as athletes who had represented their country at international competition. One team was comprised of two male riders and one team comprised two female riders. The men’s front rider was 1.87 m tall, 90 kg in weight and 37 years of age. The male rear rider was 1.76 m tall, 61.3 kg and 38 years of age. The female front rider was 1.73m tall, 54.5 kg and 35 years of age. The female rear rider was 1.74 m tall, 48.8 kg and 25 years of age. The composition of these tandem teams was the same as those seen in conventional competition. This is whereby the front rider is typically able-bodied and sighted whereas the rear rider will possess some level of physical impairment. Both teams were currently competing at international level in paracycling. The male and female teams were measured on two separate occasions and spread three months apart from each other. The male team utilising their track and their road time trial bicycles were investigated on the first occasion (event 1). The female on their road/time trial bicycle were investigated on the second occasion (event 2). An example of the athletes, testing environment and the set-up is shown in Figure 1.

[INSERT FIGURE 1 HERE]

All participants in this case study provided informed consent. The study was approved by the institutional ethics committees at the author's home institutions (no. 40627 and KEBN21-67-MS).

Statistical analysis

To investigate the precision of the wind tunnel test method when applied to tandem cyclists, six measurement periods were undertaken by the male tandem team on their road time trial bicycle at the start of event 1 and the female team on their road/time trial bicycle at the start of event 2. An average of these runs was taken and a standard deviation calculated to provide error bars. The Coefficient of Variation was used to help demonstrate the variability of these test runs. This is defined as the Standard of Deviation divided by the Mean Average and then multiplied by 100 to express it as a percentage. In the case of the male tandem team specifically, their track and their road bicycle six run precision results were also checked for their statistical significance from each other as an act of casual interest via a post-hoc *t*-test. Statistical significance for this was defined as p=<0.05.

Results

The wind tunnel precision experiment of the male track bicycle tandem team in event 1 produced a mean CdA of $0.285^{+/-0.005}$ m^2 (CV=1.6%). The wind tunnel precision experiment of the male road time trial bicycle tandem team in event 1 produced a mean CdA of $0.338^{+/-0.006}$ m^2 (CV= 1.8%). The two bicycles in event 1 that utilised the same athletes obtained results that were statistically significant from each other (P=<0.0001). The wind tunnel precision experiment of the female road/time trial bicycle tandem in event 2 produced a wind tunnel test mean CdA of $0.346^{+/-0.009}$ m^2 (CV= 2.6%).

The CV results of the aerodynamic interventions for the male team all fell within those obtained from the aforementioned precision results. The results of the aerodynamic interventions are summarised in Figures 2 and 3.

[INSERT FIGURES 2 & 3 HERE]

The results in Table 2 show that the most beneficial intervention to the male team when riding their track bicycle was to lower its front handlebars whereas the same team on the road bicycle obtained the greatest drag reduction from both riders lowering their heads.

The aerodynamic interventions for the male team are expressed as a percentage reduction in aerodynamic drag from the baseline condition in Table 2.

[INSERT TABLE 2 HERE]

Discussion

The level of precision that the male tandem team obtained in this study was twice as high as those recorded by other paracyclists[9] but still below the maximum CV of 2% recorded by able-bodied cyclists[14] and would therefore be considered satisfactory. However, the female tandem team in event 2 reported a CV that was in excess of this. This may highlight a need for riders to possess suitable prior wind tunnel riding experience, or that with some tandem teams the extra rider and larger bicycle over that of a solo rider may in some cases decrease the precision of the experiment. Neither team as specified had been in a wind tunnel prior to this study. The differences between the two teams may also have been the result of confounding factors based upon the different bicycles and equipment between them. Either way, it is proposed that the wind tunnel method is deemed suitable for aerodynamic drag assessment use in general but it should be noted that the ability to measure the magnitude of any aerodynamic intervention may rely on the team's experience or familiarity with the equipment that is being assessed. It is conceded that more participants would have provided more robust data and findings in this paper but the relatively small population pools of available paracyclists have been reported as typical of the field.[15]

Further wind tunnel testing of paracyclists is required to ascertain the test methods suitability with a greater number and range of participants.

The values reported by the tandem teams in this study are not considerably higher than those reported when wind tunnels have been used to assess individual riders.[16] In this review, 10 wind tunnel studies of individual male riders saw CdA values ranging from 0.17-0.34 in a time trial position and 0.25-0.34 in a conventional crouched position. The CdA results of 0.285 and 0.338 respectively in this paper fell within this same range. In a subsequent review of male riders,[11] a CdA range of 0.20-0.26 for time trial positions and 0.27-0.33 for a crouched position was reported. The values of 0.285 and 0.338 reported in this paper are only fractionally higher than this. As a result, the addition of a second rider and a larger bicycle does not seemingly scale up the resulting aerodynamic drag by a considerable value. This is possibly because the rear rider is partially shielded by the front rider and that the bicycle itself is a smaller proportion of the overall surface area than the riders themselves. Of the studies that have investigated tandem riders specifically when using wind tunnels or computational fluid dynamic methods, the CdA values obtained have been 0.314 when the tandem team is crouched, 0.293 when in a time trial position[11] and 0.308-0.39 when crouched.[12] While the data in this paper does not appear out of step from these studies at face value, caution is advised as it is argued that different aerodynamic studies using different wind tunnels should not be directly compared to each other.[8] This is potentially due to different blockage ratios, turbulence intensities, size and protocol for each wind tunnel.[11]

It was interesting that such a large disparity in overall CdA was seen between the track and road time trial bicycles for event 1 when ridden by the same athletes. However, it could not be guaranteed that this is solely due to the bicycle design itself as there could be several other confounding factors. For example, both bicycles were not checked for the various contact points by the athletes and the various components such as wheels and handlebars were different between the two. Furthermore, a road-based bicycle possessed additions such as derailleur gears, bottle cages and braking systems whereas as a track bicycle possesses none of those components. All of these factors would account for some disparity between the two bicycle scenarios.

It was noted that several aerodynamic interventions for the male team, whilst beneficial, demonstrated improvements that fell within the standard deviation of the wind tunnel test methodology. This does not mean that they should be discounted nor seen as insignificant. However, it would be proposed that such gains are verified using multiple measurement events or confirmed via complementary field-testing methods.[8] It is conceded that such verifications can prove challenging in reality due to the relative geographical lack and costs of wind tunnel facilities[9] or the time required to undertake them. It should be noted that the cyclists were tested at a wind yaw of zero degrees when in reality a broader range of yaw would be evident with cyclists.[17] However, a broader range could not be undertaken in this study due to the length of the tandem bicycle and the limitations of the wind tunnel design itself. This would subsequently affect the magnitude and potency of the interventions undertaken in this study when in certain conditions.

The greatest percentage reduction in aerodynamic drag of the track bicycle was as a result of lowering the front handlebars (7.4%) or in encouraging both riders to lower their heads (5.3%). Alternatively, on the road bicycle this was achieved by having the rear rider lower their head alone (5%). It should be noted that lowering handlebars still indirectly affected the head height and body position. Either way, this case study has shown that a reasonably simplistic and financially cost-effective method of altering the head position can still yield an effective performance improvement.

Whilst the time savings obtained by the aerodynamic drag reductions could be estimated by solving formulae such as those proposed by Martin et al.,[7] these don't always provide information that could be understood in context or account for the variability that event courses and riding behaviour can provide. As a result, to place the results of this case study into a ‘real life’ context, a cycling modelling app (Mywindsock, UK) was used to estimate the impact of the aerodynamic improvements in this study. A model of the 2021 Paracycling World Championship 33.6km time trial course in Cascais, Portugal held on the 10th of June, 2021, was created using this app. The geographical source data for this was obtained in the event itself and was recorded by athletes using a computer mounted on their bicycle. The male tandem team from the earlier case study in this paper participated in this event and were used as the basis of the simulations. The tandem teams’ baseline CdA of 0.338 was applied, the athlete/bicycles total mass was assumed to be 175 kg, the coefficient of rolling resistance assumed as 0.004 and the average power output was then matched to obtain the tandem teams finishing time that was recorded from the events official results (http://www.rsstiming.com/Resultats/UCIPara/RoadWCh/2021Cascais/doc/2021-Cascais-Wch-OfficialBook.pdf). As an example, by applying the 0.017 m^2 drag reduction found by lowering the male teams’ rear riders head, it was calculated that the athletes would have reduced their completion time for the event by ≈ 44 seconds. It is worth noting that 14 of the 17 teams that completed this event would also improve their finishing position with this level of gain and ultimately would affect who won medals in this event. While this example is merely a casual discussion point and used software that has not been formally peer-reviewed, it does demonstrate how a reasonably simple change in head position could be seen to arguably impact the athletes results. Therefore, not only is the continuous improvement of aerodynamic drag reducton seemingly worthwhile but that such interventions do not neccasarily need to be expensive or complicated.

Conclusion

Two teams of tandem paracyclists performed a series of test runs to investigate whether a wind tunnel is a suitable method of assessment of their aerodynamic drag. The experiments provided evidence that it was a suitable tool for this task and provided data that was broadly in line with previous studies that have reviewed individual able-bodied cyclists.

The second part of this investigation acted as a case study by implementing a range of aerodynamic interventions to potentially reduce a male tandem teams aerodynamic drag. It was illustrated that even a simplistic change such as lowering the rear riders head provided an effective performance enhancement. This demonstrated that whilst tandem cyclist performance enhancement has only recieved scant attention in the past, such interventions may be worthwhile to them in the future.

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