# The aerodynamic impact of a range of prostheses designs when cycling with a trans-tibial amputation

Previous studies have proposed that an aerodynamically optimised prosthetic limb could provide performance enhancement for competitive paracyclists. Four different designs of prosthetic limbs were assessed for their impact upon the aerodynamic drag of an elite cyclist with a lower-limb amputation. The pylon area acted as the controlled location for the differences in design between the test prostheses. A validated field test method was used to derive the participant’s total aerodynamic drag when using the prostheses designs. The field test method produced a repeatable experimental process and demonstrated that small changes in form made to the pylon region resulted in measurable differences to the participant’s cycling performance. In addition, statistical significance was obtained between a baseline design and the prostheses prototype with the greatest aspect ratio ($p$=<0.05). The magnitude of improvements recorded in this study could potentially influence a rider’s finishing time at international sporting events like the Paralympic Games.

## Implications for Rehabilitation

- Small changes in form made to a cycling prostheses design can potentially deliver worthwhile performance enhancement.
- Prosthetists may obtain greater end-user satisfaction by taking a broader approach to sports prostheses design than just fit and biomechanical function alone.
- This study indicates that other regions of the cycling prosthesis could now benefit from aerodynamic optimisation with the aim to further improve paracycling performance.

Keywords: prostheses; cycling; aerodynamics; performance enhancement

## Introduction

Previous studies have proposed that the grounds for the performance enhancement of cyclists with lower limb absence may be possible [1]. However, there is currently limited peer-reviewed literature available to help inform the clinicians with the design of assistive technology [2]. The role of aerodynamics plays a vital role in competitive cycling [3] and when at racing speeds, overcoming aerodynamic drag can represent upto 96% of the cyclist's power [4]. It has also been found that 31-39% of the wind resistance or *drag* is due to the bicycle equipment itself [5]. Therefore, any reduction in the riders' aerodynamic drag would ultimately allow a cyclist to move at the same speed for less energy expenditure or to achieve a higher riding speed at the same energy expenditure. Therefore, it could be seen as worthwhile for the design of a lower-limb prosthesis to be shaped advantageously over that of the equivalent human shank foot segment. A recent study has investigated the simulated impact of prosthetic limb design [6]. This study demonstrated that when using simulated data, a prosthesis that is aerodynamically shaped could be advantageous over one that is not. However, these simulations were not validated in reality. Two subsequent studies attempted to address this limitation. The first of these measured simulated prosthetic component-level changes made to a conventional bicycle and then assessed using a field test method. The outcome of this was that relatively small changes could still be reliably detected [1]. The second of these successfully validated a velodrome-based aerodynamic field test approach against a wind tunnel reference method [7]. However, this validation study utilised prostheses that possessed relatively large differences in design between them. To maximise a cyclist's performance, subtler or smaller incremental changes in design may well be required. In this paper, four controlled design changes are imposed on the pylon region of below-knee prosthetic limbs to determine if subtler changes are detectable and significant from each other.

## Methods

A 33 year old male paracyclist with a unilateral lower-limb amputation on his right side was recruited to participate for this experiment. They had a height of 1.72m and a weight of 73kg. This participant was an international standard track and road para-cyclist who had personal best cycling performances including 21 minutes and 31 seconds for a ten mile individual time trial and 3 minutes and 56 seconds for the three kilometre individual track pursuit. The participant provided informed consent and the author obtained institutional ethics approval for this study.

### *Test protocol*

The *Virtual Elevation* (VE) method was used to assess the aerodynamic differences between the prostheses designs. The VE method is a field test approach which has been derived from fundamental principles and subsequently validated against a wind tunnel reference method [7]. The methodology outlined in that previous study was adopted for these experiments. The VE method records a moment-by-moment speed and power output from a lap (or laps) ridden over a known route. From this, it constructs an elevation profile for the ride as a function of known power, speed, mass and air density using initial guesses of aerodynamic drag (CdA) and the coefficient of rolling resistance (Crr). Since each lap would start and end at the same point, the CdA value is altered until it produces a zero net gain in elevation over each lap. By achieving this, the assumed CdA value (and therefore the aerodynamic drag) is perceived as correct. The power (in Watts) needed to propel a rider at speed (in metres per second) is the total of the power to overcome rolling resistance, the power to account for the change in elevation (the potential energy), the power to account for a change in speed (the kinetic energy) and the power to account for air resistance. This formula [7] was defined as:

$$s = P/(mgv_{ground}) - C_{rr} - a/g - (\rho CdAv_{ground})/(2mg)$$

Where:

$s$ = slope

$P$ = Total Power

$C_{rr}$ = Coefficient of rolling resistance

$m$ = total mass (kg) of rider and bicycle

$g$ = 9.81m/sec²

$v_{ground}$ = ground speed (m/s)

$a$ = acceleration

$\rho$ = air density

$v_{air}$ = air speed of the bike

$CdA$ = drag area of the rider and bicycle

The Crr value was ascertained from previous trials [7] and was defined as 0.004. The total mass of rider and bicycle was circa 86kg with some deviation from this dependant on the slightly different weights of each test prosthesis. The power output of the rider was then captured using a 'Powertap' rear wheel hub-based power meter (Powertap, Madison, WI, USA) which has a manufacturer's proposed accuracy of ±1.5%. The use of this power meter has been validated against other such devices [8]. The sampling rate of this device was 100Hz and a wireless ANT+ protocol was used to transmit a sampling rate of 1Hz to a Garmin 500 wireless GPS unit (Garmin, Kansas, US). The virtual elevation data was obtained using a Garmin speed sensor mounted to the bicycle and then transmitted to the Garmin 500. All devices were zeroed according to the manufacturer's instructions prior to each test run.

The aerodynamic field tests took place on an indoor 250m velodrome. This type of environment has been validated for aerodynamic testing [9]. Data from the nearest weather station was used to calculate the air density. The air density value was derived from a calculator provided from a previous study by Martin et al. [10]. The air temperature was 22ºC, the dew point 10ºC, the pressure was 1016mb. This then produced a calculated air density (Rho) of 1.198. The participant rode their own time trial bicycle on the velodrome and wore the same clothing and helmet for all of the trials. No other riders were present on the track at any time during the testing so as to avoid creating any unwanted additional air flow or turbulence. All tests on the velodrome were performed on the same day.

The experiment protocol first required the participant to fit a test prosthesis at the trackside. They then mounted their bicycle and undertook a test run that involved 20 laps of the velodrome. This meant each test run equated to a riding distance of 5km. During each 5km trial, the participant cycled at 3 predetermined targeted riding speeds of 42km/h, 38km/h and 34km/h. These were primarily controlled by the rider but directed by the researcher positioned at the trackside. A range of test speeds has been recommended when performing aerodynamic field testing [7][10]. The selected test speeds were typical of those performed in racing with a disability but were also felt to be sustainable by the participant over the full length of the experiment when riding on a velodrome. Each 5km run was broken down as 6 laps targeted at 42kph followed by 1 lap to slow down and establish a new cruising speed. This was followed by another 6 laps at 38kph followed by another lap to slow down and establish the next targeted steady state cruise speed. Finally, there were 6 laps performed at 34kph. After this had been completed, the rider reduced their velocity to rest, dismounted the bicycle and then swapped the test prosthesis for another before then undertaking the next 5km test run. Two test runs of each leg design at each velocity were performed. This meant that each leg received 6 separate test intervals.

The total aerodynamic drag for the rider when using each prostheses design were reported as means with a calculated standard deviation. The Coefficient of Variation (CV) was calculated to ascertain the level of data variability for each prostheses design and expressed as a percentage. Statistical significance was also determined by a single factor ANOVA and supported by post-hoc paired *t*-tests between all of the prostheses designs. The level of statistical significance was defined as $p=0.05$.

***Prosthetic limb designs***

Four designs of prosthetic limbs formed the basis of these tests. The socket region from its limb entry to the base of the valve was standardised in terms of its dimensions. Likewise the ‘foot’ region of the prosthetic limbs were also standardised in design. All four limbs were manufactured using an identical process and using the same materials. The pylon region began 80mm up from the base of the foot of the prosthesis, was 270mm long and this specific area formed the key difference between the four designs. It is conceded that the transitions of shank area to both foot and socket areas were unique with each design due to the distinct pylon profile and depth of each prosthesis. The width of each pylon of all four designs was standardised as 18mm. Only the depth and profile of the pylon region was altered between the four designs.

The four designs included:

(1) *A round section design*. This was defined as the ‘baseline’ design for the purposes of these tests. It had a pylon that was round and 18mm in diameter.

(2) *A 3:1 aerofoil design*. This was an aerofoil 18mm in width, 54mm in depth. The aerofoil profile itself was a standardised NACA 0012 design obtained from an online creative resource [11] and was modified to assume a strict 3:1 aspect ratio. The 3:1 ratio was selected for philosophical reasons as this is the current maximum aspect ratio allowed by the sport’s governing body for bicycle components. Whilst cycling prostheses by themselves are not defined as bicycle components per se’, it has been inferred that similar regulations might be applied to them in the future [12].

(3) *A 6:1 aerofoil design*. This was an aerofoil 18mm in width, 108mm in depth. The aerofoil profile itself was a standard NACA 0012 design obtained from an online creative resource [11]. A 6:1 design was selected as it had an incremental relationship to the 3:1 design (e.g. being twice as deep).

(4) *A 6:1 Kamm aerofoil design*. This design was identical to the 6:1 aerofoil. However, a Kamm tail feature was then applied to the aerofoil making it 18mm in width and 87mm in depth. A Kamm tail is an aerofoil which is cut when the width of the aerofoil (as it tapers down) reaches 50% of the aerofoil’s maximum width. Therefore, in this case, the cut was taken when the cross section width was 9mm. Due to this cut, the aerofoil has a flat back face. The Kamm tail design is a notable design feature

originating in automotive engineering [13] and more recently used in bicycle frame design by the Trek company [14]. This design was selected as it has a relationship to the 6:1 design and the Kamm method has been proposed to demonstrate many of the aerodynamic advantages of a complete aerofoil shape but in this case would not exhibit an aspect ratio depth that might make it appear visually unpalatable to the sport.

Images of the four test prostheses in side profile are shown in figure 1.

[INSERT FIGURE 1 HERE]

The prostheses testing running order was randomised. The running order was therefore determined to be prostheses design 1, 4, 3, 2, 3, 1, 4, and 2.

Finally, the participant used the same prosthetic liner when wearing any of the test prostheses. The liner was an Ossur Sealin X5 (Ossur hf, Reykjavik, Iceland) coupled with an Ossur L-551002 valve (Ossur hf, Reykjavik, Iceland) to provide suction suspension.

**Results**

The test runs were all completed as prescribed. However, the participant reported some alignment-based discomfort with prosthesis 4 during the testing. It was felt that this perceived discomfort could ultimately affect its results. In response to this, after the main tests were concluded, some minor adjustments were then made to the cleat (this attaches the leg to the pedal) and the fit alignment of prostheses 4. As a result, an additional run involving three test intervals with these modifications were then undertaken. Only three intervals could be completed due to the limitations of time. A comparison of the CdA's and CV's produced by the rider from the four designs are shown in table 1.

[INSERT TABLE 1 HERE]

The calculated CV(%) of the tests of each design is in the 2-3% range and this would be considered very low when field testing. This suggests that the participant achieved a high level of repeatability in their calculated aerodynamic drag and this would likely be due to them being able to hold the same riding position when undertaking all of the test runs for a given prosthesis. The calculated CdA's of each speed of the 4 designs are illustrated graphically in figure 2.

[INSERT FIGURE 2 HERE]

In fig 2, it can be seen that the adjusted version of prosthesis 4 produced the greatest reduction to the participant's total aerodynamic drag. However, since this prosthesis only saw three rather than six test runs (as per the other designs), this result should be treated with some caution. If the results from prosthesis 4 are discounted, prosthesis 3 produced the next greatest reduction in overall aerodynamic drag.

Use of ANOVA demonstrated statistical significance between the five tested configurations ($p$=0.02). However, the post-hoc $t$-tests revealed that the only designs that were statistically significant from each other were prostheses 1 and 3 ($p$=0.02), prostheses 1 and 4 (adjusted version) and prostheses 3 and 4 ($p$=0.02). From this, design 3 was proposed to be the most statistically reliable and significant performance enhancement of the four designs.

## Discussion

Of the four designs, the adjusted version of prosthesis 4 produced the greatest reduction to the participant's total aerodynamic drag. This suggests that if optimised, the 6:1 based Kamm design might perform nearly as well as the full 6:1 aerofoil design, despite the removal of some of its tail. However, it is conceded that more time would be required to validate this particular finding as the adjusted version of prosthesis 4 lacked a comparable level of statistical power to the other designs. Nonetheless, the experience of the adjustment process to design 4 is a useful one for clinicians to note, as this stresses both the sensitivity and importance of lower-limb prosthetic alignment. If the misalignment is substantial enough, the aerodynamic benefit of the Kamm aerofoil design was lost entirely. In lieu of these issues, prosthesis 3 would yield the greatest level of performance enhancement to the cyclist with limb absence. Designs 2 and 4 also demonstrated a reduction in aerodynamic drag yet did not obtain statistical significance. However, other forms of competitive sports have recognised that non-norm levels of *p* may be required when comparing sports technology [15]. By doing so would reflect the close finish nature of elite-level competition and the impact that sports equipment can have upon it. Ultimately, the specification of any *p* value could be arbitrary in nature so it is recommended that future research investigates this further.

As a result of the testing in this study, it might be worthwhile to assess aerofoil profiles that are even deeper in aspect ratio than 6:1. The appropriate ratio could be ascertained mathematically using the targeted riding speed, but it is a complex problem due to the fact that the cyclist's legs are constantly moving and may vary in their orientation and angle of attack at every part of the pedalling stroke. There may also be interaction aerodynamically between the rider and their bicycle, since multiple objects in close vicinity can influence the air flow (and subsequent drag) of each other [16]. As a result, the optimum design may vary from rider to rider. This could only be ascertained once such tests are applied to a larger pool of participants. However, whilst small participant pools would typically be seen as undesirable, this is a common reported limitation when investigating cycling with a physical disability [17][18][19]. As a result, a computational fluid dynamic (CFD) approach using a modelled rider of varying sizes and a variety of prosthesis designs might be a practical and cost effective alternative to the issues surrounding airflow interaction and small participant pools.

The results obtained from this study could be applied to suggest the time saved in a typical Paralympic Games event when applying a series of basic assumptions. For example, at the 2012 Paralympic Games, the individual time trial event that this participant would have raced over would have been approximately 16km/10 miles in length. By using the participant's recorded CdA from this papers experiment, their typical power output as 300w, their mass of 73kg and when riding on a smooth surface, the following estimated finishing times for a flat time trial course were calculated. These are shown in table 2.

[INSERT TABLE 2 HERE]

It should be noted that at the 2012 Paralympic Games, the difference between the gold and silver medal in the C3 category was 9 seconds, the silver and bronze medals 24 seconds, and the bronze and 4$^{th}$ place 14 seconds [20]. Such gaps are not dissimilar to the potential improvements identified in this paper between the baseline test prosthesis 1 and some of the other designs. The gains proposed in table 2 would potentially allow any rider currently not using an optimised design (or using a round section prostheses similar to that of the baseline test prostheses 1), to potentially be able to improve their results.

Whilst this study only assessed changes made to a defined area of the prostheses, it has nonetheless demonstrated that there is potential scope for performance enhancement for para-cyclists who may be using traditional or wholly functional prosthetic limb designs. If other areas (such as the ‘foot’ or the socket) were also altered, this could lead to further performance enhancement. In addition, whilst this study’s emphasis was on elite sport, this awareness allow clinicians the ability to create assistive technology that would allow anyone who wishes to cycle with lower-limb absence, the ability to do so with reduced energy expenditure.

## Conclusions

An elite male paracyclist was assessed for changes in his total aerodynamic drag when riding using a range of lower-limb prostheses. Use of a field test method to detect changes in aerodynamic drag produced a high level of precision for all four designs. The experiments demonstrated that subtle changes made to the pylons shape produced statistical significance between prostheses that had a deep aerofoil design compared to those of a round section. Therefore, this design change produced a worthwhile reduction in the cyclists’ total aerodynamic drag. The magnitude of these results demonstrated that the calculated gains illustrated in this paper could potentially influence the results of elite paracycling competition.

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**Declaration of Interest**

The authors report no conflicts of interest

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