The effect of upper body positioning on the aerodynamic-physiological economy of time trial cycling.

Original Investigation

Steve H. Faulkner and Philippa Jobling

Department of Engineering, SPEED Laboratory, Nottingham Trent University, Clifton Campus, Nottingham, NG11 8NS, UNITED KINGDOM

Corresponding author:

Dr Steve H. Faulkner,
Department of Engineering,
SPEED Laboratory,
Nottingham Trent University,
Clifton Campus,
Nottingham,
NG11 8NS,
UNITED KINGDOM

steve.faulkner@ntu.ac.uk

Running head: Aerodynamic-Physiological Economy

Abstract Word Count: 236

Text-only word count: 4,723

Number of figures: 5

Number of tables: 1

Abstract

Purpose Cycling time trials are characterised by riders adopting aerodynamic positions, to lessen the impact of aerodynamic drag on velocity. The optimal performance requirements for time trials likely exists on a continuum of rider aerodynamics versus physiological optimisation, yet there is little empirical evidence to inform riders and coaches. The aim of the present study was to investigate the relationship between aerodynamic optimisation, energy expenditure, heat production and performance. **Methods** Eleven trained cyclists completed five submaximal exercise tests, followed by a time trial. Trials were completed at hip angles of 12° (more horizontal), 16°, 20°, 24° (more vertical) and their self-selected control position. **Results** The largest decrease in power output at anaerobic threshold compared to control occurred at 12° (-16±20W, P=0.026; ES=0.8). There was a linear relationship between upper body position and heat production (R^2=0.414, P=0.037) but no change in mean body temperature, suggesting that as upper body position and hip angle increase, convective and evaporative cooling also rise. The highest aerodynamic-physiological economy occurred at 12° (384 ± 53 $W \cdot CdA \cdot L \cdot min^{-1,}$ ES = 0.4) and the lowest at 24° (338 ± 28 $W \cdot CdA \cdot L \cdot min^{-1}$, ES = 0.7), versues control (367 ± 41 $W \cdot CdA \cdot L \cdot min^{-1}$). **Conclusion** These data suggest that the physiological cost of reducing hip angle is outweighed by the aerodynamic benefit. |These data suggest that riders should favour aerodynamic optimisation for shorter time trial events. The impact on thermoregulation and performance in the field requires further investigation.

Keywords: aerodynamics, thermoregulation, electromyography, performance, engineering

Introduction

Cycling time trials are characterised by riders adopting optimal aerodynamic positions on the bike in order to lessen the impact of aerodynamic drag on the rider's velocity. Time trial events can vary in both length and duration, ranging from a 4,000m individual pursuit completed in a velodrome lasting approximately 4-5 minutes, up to 100 miles or more on the road, lasting in excess of 4-5 hours. It is likely that the optimal performance requirements for events of such divergent distances and durations exists on a continuum of ride aerodynamic versus physiological optimisation.

Cycling speed is determined by a rider's power output, aerodynamic drag (CdA), road surface, and environmental conditions.[1] With the force required to overcome aerodynamic drag being calculated using the formula:[2]

$$F = \frac{1}{2} \rho v^2 \, \mathrm{CdA}$$

Where F is the total drag force (N), ρ is the density of air (1.2 $\mathrm{Kg{\cdot}m^{-3}}$ at sea level), v is the speed of the air relative to the rider and bike ($\mathrm{m{\cdot}s^{-2}}$), Cd is the drag coefficient (dimensionless) and A frontal area ($\mathrm{m^2}$). Traditionally, riders and coaches have focused primarily on the development of higher power output during cycling to increase speed. Recently, a greater focus on reducing CdA has become apparent, as 80-95% of the resistive forces experienced during cycling occur as a consequence of the rider and their equipment.[3] Despite this, a key factor that is currently poorly understood is the exact relationship between aerodynamic optimisation, the physiological cost and the overall performance outcome.

Riders who adopt an aerodynamic position often do so by reducing torso or hip angles,[4,5] lessening the airflow over and around the body. Hence riders experience a reduction in aerodynamic resistance and can travel faster for a given power output at a reduced metabolic cost.[6] Altering rider position to favour aerodynamics likely hinders the critical power (CP) that a rider is able to sustain. It has been demonstrated that by moving from riding on the hoods of the handlebars, to a time trial position, a rider's CP is reduced.[7] This reduction in CP is likely multifactorial and related to changes in oxygen consumption, muscle blood flow, muscle activation and gross efficiency.[8–11] For example, a lower hip angle may result in a reduction in muscle activity,[9] and subsequently power output[4], in the lower limb owing to an alteration in the length tension relationship during the pedal cycle[9]. However, data concerning this are equivical.[8,12,13] Therefore, if the gain from optimising aerodynamics does not outweigh the potential physiological cost of reducing hip angle, then time trial performance will not improve. Moreover, given the relationship between speed and the power output required to overcome aerodynamic drag, shorter faster events likely have a greater reliance on aerodynamic optimisation, whereas longer duration time trials may require greater consideration for individual rider physiology and environmental conditions.

In conditions where ambient temperature is high there is a reliance on the evaporation of sweat to help maintain heat balance during exercise. Although the high speeds associated with cycling are conducive to increasing sweat evaporation,[14] it is possible that a reduction in air flow over the body, as a result of aerodynamic positioning, could inhibit heat loss via reduced sweat evaporation. If heat loss is inhibited then an increase in heat storage is inevitable, which may result in a reduced performance capacity, especially in longer duration time trials[15] or triathlon events. Currently, the exact balance between aerodynamic optimisation versus the physiological cost is unknown, and a sensitive measure encompassing both the aerodynamic and physiological components of cycling is absent.

The overarching objective of this study was to begin to better understand the complex interaction between aerodynamics, power production and thermoregulatory effects during simulated time trial cycling. The primary aim of the present study is to investigate the relationship between hip angle, thermoregulation, economy and performance. A secondary aim is to develop a unit of measurement that is sensitive to changes in rider position with respect to their aerodynamic and physiological economy. It was hypothesised that there would be a reduction in power output at lactate threshold as hip angle decreased. The secondary hypothesis was that changes to physiological parameters in response to hip angle manipulation would impact aerodynamic-physiological efficiency and thermoregulation.

Methods

Participants

Eleven well-trained male cyclists, with a history of competing in time trials and/or triathlons for more than five years, volunteered to participate in this investigation (Table 1) and were equivalent to performance level 3.[16] All participants were free from injury, familiar with the type of testing involved.

During the testing period, participants were asked to maintain their normal training and to refrain from heavy exercise, caffeine and alcohol during the 24-hours prior to each laboratory visit. Each participant completed their sessions at the same time of day to minimise the effects of circadian and diurnal rhythms on performance and physiological measurements, with individual sessions being separated by a minimum of 7 days.

The study was approved by the ethics board at Nottingham Trent University and performed in accordance with the Declaration of Helsinki. Participants provided their written informed consent prior to testing.

****table 1****

Study Overview

Participants visited the laboratory on 7 separate occasions. The first visit involved the determination of each participant's time trial position from their own bike for replication on the laboratory ergometer and the collection of anthropometric data (table 1). Hip angle was determined using a goniometer, with the fulcrum at the *greater trochanter* at the head of the femur in line with the *acromion process* on the scapula, horizontally to the floor. Hip angle was measured with the rider positioned in the TT position, with their lower limb at the bottom of the pedal stroke. Frontal area (A) was determined using a digital representation of each rider's frontal projected area in each of the prescribed positions. Riders' bikes were mounted on a stationary turbo trainer placed on a photographic green screen, with the stem positioned 2.2m from a digital camera (Bioracer Aero, Bioracer motion, Belgium). A digital image was obtained of each rider with their right leg at the bottom of the pedal stroke. The integrated software was then used to calculate the frontal area of the rider. Anthropometric data and the measured frontal area where then used to estimate each rider's coefficient of drag (Cd):[17]

$$Cd = 4.45 \cdot (Mass^{-0.45})$$

and CdA (table 1):

$$CdA = Cd \cdot A$$

Participants then performed an incremental $\dot{V}O_{2\,\max}$ test, on a cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). Participants cycled at their preferred cadence, starting at 95W, with a 35W increase in power output every three minutes until volitional fatigue. $\dot{V}O_2$, $\dot{V}CO_2$, RER and HR were recorded continually throughout the test, with data averaged over the final 30s of each stage.

The second visit acted as a familiarisation to the time trial protocol (TT; see below) to minimise the potential learning effects on the performance measurements. The subsequent 5 visits consisted of a submaximal exercise test to a fixed lactate threshold of 4 $\text{mmol} \cdot \text{L}^{-1}$ (LT) followed by a TT, each at hip angles of 12°, 16°, 20°, 24° and control (self-selected TT position), in relation to the horizontal plane. The desired angles were achieved by alteration of handlebar height and reach. Participants were blinded to the conditions as far as practicable, and to minimise order effects, a balanced experimental order of the five conditions was used.

Experimental Protocol

An ingestible telemetric temperature pill (CoreTemp, HQ Inc., Palmetto, FL, USA) was given to participants to allow for the measurement of gastro-intestinal temperature (T_{gi}) and swallowed 8-10 hours prior to start of all 5 of the main trials. Pill function was verified upon arrival to the lab using a receiver and its position in the gastro-intestinal tract was confirmed by the ingestion of water. Nude body weight was recorded (Adam Equipment Co. Ltd., Milton Keynes, UK) and wireless thermistors (iButton, DS1922, Sunnyvale, CA, USA) were secured to the skin. Muscle activity in the *rectus fem*oris (RF), *biceps femoris* (BF) and *medial gastrocnemius* (MG) was recorded using wireless EMG sensors (DataLite, Biometrics Ltd., Newport, UK; 2000Hz). All participants were given a standardised triathlon suit (Huub, Derby, UK) in order to standardise the effect of textile insulation on skin and ensure comparable airflow effects owing to the clothing.

Submaximal Exercise Test

The submaximal test followed the same procedure as described for the $\dot{V}O_{2max}$ test, however the test was terminated once the participant reached LT. Fingertip blood lactate samples were collected into 20µl capillary tubes, at rest and during the last minute of each stage and analysed immediately (Biosen, EKF Diagnostics, Cardiff, UK). Rate of perceived exertion (RPE),[18] thermal comfort (TC),[19] thermal sensation (TS),[20] heart rate (Polar, R400, Kempele, Finland) and T_{gi} were recorded in the final minute of each stage. Upon test termination, all participants completed a standardised 5-minute active cool-down at 100W.

Time Trial

Following 30-minutes passive recovery, participants performed a standardised 11-minute warm up prior to the TT (6 minutes at 50% W_{max}, 2 minutes at 60% W_{max}, 2 minutes at

70% W_{max} and 1 minute at 80% W_{max}). Following 5 minutes rest, the riders began the TT. Participants were given a set amount of work, equivalent to cycling for 20 minutes at 75% W_{max} (321.4 ± 38.0 kJ) to complete in as fast a time as possible. The ergometer was set in linear mode so that 75% W_{max} was obtained when participants cycled at their preferred cadence, as established from the $\dot{V}O_{2max}$ test. Target workload was calculated as:[21]

$$Target\ Workload\ (kJ) = \frac{(0.75 \cdot W_{max})}{1000} \cdot 1200$$

During the time trial, participants were allowed to drink water *ad libitum*. Water was kept at the same temperature as the surrounding environment. For every 25% of target workload completed, split time, power output, T_{gi}, HR, cadence, RPE, TC and TS were recorded. No specific performance feedback or encouragement was given during the TT. Participants could only view workload completed, workload remaining and a graphical representation of fluctuations in power output. Upon completion, nude weight, fluid consumed and skinsuit weight were measured to calculate fluid intake and sweat rate.[22] Throughout both the submaximal exercise test and the time trial, mean wet globe dry bulb temperature was 18.6 ± 1.6°C and air flow 2.5 $m{\cdot}s^{-1}$ generated by a vertical bank of 3 fans.

Data Analysis

Aerodynamics

The Cd and A for each rider in their self-selected control position was calculated (see above). Given that Cd is difficult to measure in the absence of a wind tunnel and is largely determined by changes in overall rider profile, we estimated riders' CdA based on their projected frontal area as described previously in this section. The power achieved at LT for each condition was then used to determine each rider's $W{\cdot}CdA^{-1}$ for each hip angle. In order to gain some insight into the combination of aerodynamic optimisation and the potential physiological implications, $W{\cdot}CdA^{-1}$ was normalised to the corresponding oxygen uptake at LT to quantify aero-physiological economy (APE; $W{\cdot}CdA{\cdot}L{\cdot}min^{-1}$).

Electromyography

A high-pass filter was applied to the raw EMG data, at 50Hz. Peak muscle activation was defined by the largest average of 10 pedal revolutions during the $\dot{V}O_{2\,max}$ test. All activity was calculated relative to this figure. Mean activation of each individual muscle was calculated over 10 epochs of the EMG signal at the end of each incremental stage. During the TT, mean activation over 10 individual pedal revolutions was analysed at every 25% of completed target workload. All activity was calculated separately for each individual muscle and then summated to gain further insight into global muscle activation in the lower limb.

Thermometry

Skin temperature was measured throughout the submaximal test and TT at eight locations (forehead, chest, scapula, upper arm, forearm, hand, thigh and calf), with $\bar{T}_{sk}$ subsequently calculated.[23] Mean body temperature (T_b) was calculated as follows:[24]

$$T_b = (0.8 \text{ x } Mean\ T_{gi}) + (0.2 \text{ x } Mean\ T_{sk})$$

The rate of metabolic energy expenditure (M, W$\cdot$m^2) was calculated as:[25]

$$\mathrm{M} = \dot{\mathrm{V}}\mathrm{O}_2 \cdot \frac{\left[\left(\frac{\mathrm{RER}-0.7}{0.3}\right)\cdot \mathrm{e_c}\right] + \left[\left(\frac{1.0-\mathrm{RER}}{0.3}\right)\cdot \mathrm{e_f}\right]}{60 \cdot \mathrm{BSA}} \cdot 1000$$

Where RER is the respiratory exchange ratio, and e_c and e_f represent the energy equivalent of carbohydrate (21.13 kJ) and fat (19.69 kJ) respectively, per litre of O_2 consumed (L$\cdot$min^{-1}) and BSA is body surface area according to the DuBois formula.[26] $\dot{H}_{prod}$ (W$\cdot$m^2) was calculated as the difference in M and external work rate (W):[27]

$$\dot{H}_{prod} = M - W$$

Statistical Analysis

GraphPad Prism (version 8) software was used for all statistical analysis. Normal distribution of data was assessed by the Shapiro-Wilk test. Separate mixed methods analysis of variance (ANOVAs) were used to determine main effects of hip angle and time. Where significant differences were identified, post-hoc pairwise comparisons were conducted with a Bonferroni correction. One-way ANOVAs were used to determine the effect of hip angle on time trial finish times, mean power output and the impact on aerodynamic variables. Linear regression was used to determine the power achieved and oxygen consumption at LT for each hip angle. The accepted level of significance was $p<0.05$. All data are presented as mean ± SD unless otherwise stated. Magnitude-based inferences about the true (population) effect of hip angle on time trial performance were calculated. The uncertainty in the effect was expressed as 90% confidence limits (CLs) and as the likelihood that the true value of the effect represents substantial change: harm or benefit.[28] The smallest worthwhile change (SWC) in time-trial performance was calculated using standard deviation derived from the control trial data and multiplied by an effect size value of 0.2, which is equivalent to a small effect on performance. Effect sizes (ES) corrected for bias using Hedge's *g* were calculated as the ratio of the mean difference to the pooled standard deviation of the difference, with 95% confidence intervals (95% CI) for differences also presented. The magnitude of the ES was classed as trivial (<0.2), small (0.2– 0.6), moderate (0.6– 1.2), large (1.2– 2.0) and very large (≥ 2.0).[28]

Results

Coefficient of Drag (CdA)

There was a main effect of torso angle on CdA ($p<0.0001$). Control CdA was 0.222 ± 0.018 with CdA at 12° (0.215 ± 0.017), 16° (0.224 ± 0.018), 20° (0.228 ± 0.019) and 24° (0.234 ± 0.019) all being different to control ($P\leq0.01$) and each other ($P<0.001$).

Aerodynamic-Physiological Economy

There was no effect of hip angle on $W \cdot CdA^{-1}$ (P=0.418; control = 1301 ± 253W; 12°= 1270 ± 274W; 16° = 1280 ± 296W; 20° = 1266 ± 248W; 24° = 1247 ± 286W). When $W \cdot CdA^{-1}$ was normalised to oxygen uptake in order to achieve an indication of the interaction between aerodynamic positioning and metabolic efficiency, clear differences were evident. Aerodynamic-physiological economy was different between conditions ($P<0.0001$), with a higher $W \cdot CdA \cdot L \cdot min^{-1}$ value indicating higher aero-physiological efficiency (Control = 367 ± 41 $W \cdot CdA \cdot L \cdot min^{-1}$; 12° = 384 ± 53 $W \cdot CdA \cdot L \cdot min^{-1}$, ES = 0.4; 16° = 367 ± 49 $W \cdot CdA \cdot L \cdot min^{-1}$, ES = 0.1; 20° = 361 46 $W \cdot CdA \cdot L \cdot min^{-1}$, ES = 0.2; 24° = 338 ± 28 $W \cdot CdA \cdot L \cdot min^{-1}$, ES = 0.7) However, post-hoc comparisons only yielded a difference between control and 24° ($P<0.001$).

figure 1

Performance data – Time trial

There were no differences in time trial finish time at any hip angle compared to riders' control position (1108±86s; P=0.226, figure 2). However, there were small effect sizes present at 16° (1081 ± 101s, ES=0.3, -0.61 to 1.16, 2.2% faster than control) and 20° (1078 ± 73s, ES = 0.3, -0.63 to 1.13, 1% faster than control) and a trivial effect at 12° (1121 ± 125s, ES=0.12, -0.99 to 0.76, 1.4% slower than control). The difference in finish time compared to control was 13±81s at 12°, -27±48s at 16°, -20±46s at 20° and 0±61s at 24°. When considered relative to the SWC in performance, defined as being a change in performance of greater than 1.5% or 17s, qualitative inference indicates that the effect of a 12° hip angle was *possibly harmful* to performance (90% CL, -0.12, -0.41 to 0.17) with chances of a beneficial/trivial/harmful effect being 3.5%, 64.4% and 32.1%, respectively. At 16°, the inference suggested this was *possibly beneficial* to performance (0.3, -0.06 to 0.66) with chances of a beneficial/trivial/harmful effect being 67.9%, 30.9% and 1.3%, respectively. A similar inference was true for a 20° hip angle which was also *possibly beneficial* (0.25, -0.15 to 0.65), with the chances of a beneficial/trivial/harmful effect being 58.3%, 38.4% and 3.3%.

There was a main effect of time on power output during the time trial (P=0.003), whereby power tended to decline throughout the time trial. However, there was no effect of condition (P=0.152) or an interaction (P=0.174).

figure 2

Thermometry

During the time trial, there was a main effect of time on $\overline{T}_{sk}$ (P<0.0001, figure 3A) but no effect of condition (P=0.149) or interaction (P=0.243). A similar effect was evident for T_{gi} with a main effect of time only (P<0.0001, figure 3B). Consequently, mean T_b reflected these data and showed a main effect of time only (P<0.0001, figure 3C).

*****figure 3*****

Performance data – Submaximal test

Power Output

There were no differences in power output at a blood lactate concentration of 4 mmol$\cdot$L^{-1} (control = 286±42W, 12° = 271±49W, 16° = 283±52W, 20° = 286±43W, 24° = 284±62W, $P=0.222$). However, there was a moderate effect at 12° compared to control (ES=0.8) and a small effect at 16° (ES=0.2). There was also an effect of hip angle on the change in power at 4 mmol$\cdot$L^{-1} compared to control ($P=0.045$, figure 4). There were larger reductions in power output compared to control evident between 12° (-16±20W) compared to the change at 20° (-1±19W; both $P=0.026$) and 24° (2±17W; $P=0.009$, figure 4).

figure 4

Energy expenditure, heat production, economy and efficiency

There was an effect of hip angle on metabolic energy expenditure ($P=0.044$) with differences between control (1222 ± 167W) and 12° (1150 ± 166W, $P=0.048$, ES=1.74, figure 5A). There was an overall effect of hip angle on $\dot{H}_{prod}$ ($P=0.038$, figure 5B), which increased linearly with hip angle ($R^2=0.414$, $P=0.037$). However, there were no clear differences between conditions. Compared to control (936 ± 133W), effect sizes of hip angle on $\dot{H}_{prod}$ ranged from trivial at 20° (934 ± 119W, ES = 0.1), small at 16° (928 ± 147W, $P=0.808$, ES=0.2) to large at 12° (880 ± 125W, $P=0.077$, ES=1.5) and 24° (983 ± 196W, ES = 1.4).

There was no effect of hip angle on cycling economy ($P=0.22$) although there was a small effect evident at 24° (77.9 ± 5.3 W$\cdot$L$\cdot$min^{-1}) compared to control (81.5 ± 5.5 2 W$\cdot$L$\cdot$min^{-1}, $P=0.041$, ES=0.5). Similarly, there was no effect of hip angle on efficiency ($P=0.161$), although there was a moderate effect evident at 24° (21.8 ± 1.5%) compared to control (22.7 ± 1.8%, $P=0.078$, ES=0.6).

figure 5

Electromyography

Compared to control, there were no differences in the relative muscle activation of the quadriceps ($P=0.517$), hamstrings ($P=0.193$) or gastrocnemius ($P=0.170$) at a power output equivalent to a blood lactate concentration of 4 mmol$\cdot$L^{-1}. There were no main effects of hip angle on summative muscle activation for either relative ($P=0.232$) or absolute ($P=0.410$) levels of muscle activity.

Discussion

The aim of the present study was to investigate the relationship between hip angle and key physiological and aerodynamic variables that may impact on time trial performance. The main finding is that with increasing hip angle (i.e less flexion of the torso) there is a concomitant increase in both metabolic energy expenditure and metabolic heat production as power at LT increases. However, it appears that the reduction in power at lower hip angles is overcome by a reduction in aerodynamic drag and improved aero-physiological economy (APE). Practically, these data show that for short duration time trials (<~20 minutes), riders should favour optimising their aerodynamics, as any physiological cost will be outweighed by the aerodynamic benefit.

Aerodynamic-Physiological Economy

It has previously been demonstrated that hip angle and frontal area are closely related,[5] with an increase in hip angle resulting in an increased frontal area and therefore, larger aerodynamic drag. Aerodynamic drag is the air resistance that is caused by an object, with different objects having different coefficients of drag (Cd, dimensionless). A typical cyclist may have a Cd of approximately 1.2 when sat riding in a relaxed position with their hands on the tops of the handlebars, a figure that may drop to 0.7 when adopting an optimised time trial position.[29] Importantly, Cd is influenced by the frontal area of an object (A, m^2). Therefore, if you have two riders using the same clothing and equipment in identical positions, but one being smaller in stature, the smaller individual will have a smaller frontal area and therefore lower Cd per unit of frontal area (CdA, m^2). Consequently, a reduction in hip angle, and therefore frontal area, should lower CdA, making a rider more aerodynamic, owing to an overall reduction in drag. However, this only tells half of the story, as if a rider adopts an extreme position, closing off their hip angle, it may result in a reduction in power output[4,30] and impact performance, unless the aerodynamic benefit outweighs the loss in power and total metabolic cost.[30] This is important as a reduction in hip angle will likely alter muscular activation during the pedal cycle,[13,30] and more variation in body position. Both of these factors could result in accelerated rates of fatigue, particularly in longer duration events. Furthermore, as a rider travels faster, they will need to generate more power to overcome the larger aerodynamic drag forces, hence if a rider is more aero, but can’t generate sufficient power to increase speed of travel, owing to a biomechanical disadvantage, then the balance in positional optimisation is likely incorrect. Subsequently, attempting to gain a more accurate insight into the relationship between power and aerodynamics may arise from the use of power normalised to CdA ($W \cdot CdA^{-1}$), where a higher sustainable $W \cdot CdA^{-1}$ value is considered more desirable.

From the power data obtained at $4mmol \cdot L^{-1}$, a hip angle of approximately 16° appears optimal with respect to achieving the highest sustainable power. However, when you consider the relationship between aerodynamics and power output, a more aggressive position (12°) may outweigh the reduction in sustainable power at 4 $mmol \cdot L^{-1}$ compared to more open hip angles. This may result in improved time trial performance in competition where aerodynamic drag is a significant issue. This is supported by our calculations aimed at estimating the aero-physiological economy (APE) of cycling, which demonstrate that overall efficiency may in fact be increased at a reduced hip angle, where aerodynamic drag is minimised. This means that even though there are potential reductions in sustainable power output, the improvement in aerodynamics may result in overall speed being sustained, at a lower metabolic cost. We now propose a metric that can directly quantify this relationship, with a higher absolute APE ($W \cdot CdA \cdot L \cdot min^{-1}$) indicating faster performance potential.

Our data add to the limited work suggesting that aerodynamic gains outweigh the physiological and biomechanical disadvantages of a reduced hip angle in trained cyclists.[10] Previously, this has only been established at relatively low exercise intensities.[4,10] We show, for what we believe is the first time, that the aerodynamic gains outweigh potential physiological costs at intensities that are closer to true time trial efforts (~80-85% W_{max}). Further work should be conducted to establish the relationship between aerodynamic optimisation and metabolic efficiency in a more ecologically valid environment, where aerodynamics play a greater role in determining a rider's performance.

Thermal Variables

Despite an increase in $\dot{H}_{prod}$ as hip angle increased, there was no subsequent difference in mean body temperature between conditions. This may be explained by an increase in heat loss occurring due to a greater percentage of body surface area being exposed to the airflow as hip angle is increased. A rise in airflow over the body would be expected to result in an increase in both convective cooling and evaporation of sweat, helping to maintain a stable $\bar{T}_b$ between conditions. As no change in sweat rate is reported between trials, the primary mechanism increasing heat loss must be a consequence of increased surface area of evaporative cooling. This would result in an increase in forced evaporation during cycling at higher hip angles and appears to compensate for the increase in $\dot{H}_{prod}$. However, in conditions where wind (or rider) speed is reduced, or humidity elevated, the environmental evaporative cooling capacity may be impaired and hyperthermia becomes a limiting performance factor.[14,31,32] Therefore, it can be speculated that riders in longer events, such as long-distance time-trials and triathlon, may benefit from a more upright position in order to promote sweat evaporation and limit heat storage during the bike leg. A simultaneous effect will likely enhance rider comfort and reduce variance in postion during the ride, whilst having minimal effect on overall APE. Currently, there is no available literature to support this hypothesis and further research should be done to better understand the combined effects of heat and positional set up on the bike on triathlon specific performance as opposed to investigating each sport in isolation and inferring possible performance benefits.

Electromyography

During cycling, the muscles of the lower limbs are predominant in generating power.[33] It was originally hypothesised that as hip angle increased, so too would lower limb muscle activity, however, this was not the case. Despite this, it is difficult to offer an alternative explanation as to why M and also $\dot{H}_{prod}$ increase with hip angle, given that power output at 4 $mmol{\cdot}L^{-1}$ did not differ between conditions. One possible explanation is that the activity in other muscle groups were altered as a consequence of changes to hip angle.[8,9,13] In the study by Verma et al., they report that as saddle height was increased, with an assumed increase in hip angle at full knee extension, there was a concurrent increase in muscle activity and therefore metabolic energy expenditure. Furthermore, changes in saddle height have been shown to alter power production, which is suggested to be as a consequence of an alteration in the duration of activation and recruitment pattern of the major muscle involved in cycling.[9] A clear limitation in the present study is that we only record EMG in three individual muscles in the lower limb and it has been shown that lower limb EMG is sensitive to change in at least eight individual muscles.[33] This raises the possibility that muscle activity was altered in other muscles, other than those that were measured, which may explain the reported increase in M and $\dot{H}_{prod}$.

Practical Application

The application of these data relates to riders' position selection for time trial events. Our data show that a focus on aerodynamic optimisation outweighs the physiological cost of reducing hip angle on power output at lactate threshold. Importantly, the use of aerodynamic-physiological economy as a measure of overall efficiency, provides athletes and coaches with a direct way of assessing the optimal time trial position for a cyclist. Further work is needed to understand the relationship between time trial position, $\dot{H}_{prod}$ and heat storage, in order to determine the thermal effects of position that may affect performance in long duration time-trials, where performance may benefit from a less aerodynamic position, in order to help keep a rider cool by increasing airflow and evaporation of sweat.

Conclusion

Based on our estimation of riders' CdA we show that there is a clear trade-off between metabolic efficiency and aerodynamic optimisation and suggest the APE index may quantify this relationship. The reduction in power at lower hip angles is overcome by lower aerodynamic drag and improved aero-physiological economy. Furthermore, these data show that a rider's position during a time trial may influence $\dot{H}_{prod}$. We suggest that this is due to alterations in the air flow over the body, and consequently convective cooling. Practically these data show that for short duration time trials (<~20 minutes), riders should favour optimising their aerodynamics, as any physiological cost will be outweighed by the aerodynamic benefit. However, in longer duration events, where heat may become a limiting factor, adopting a less aerodynamic position may help to increase heat loss during cycling.

Acknowledgements

The authors would like to thank Jacob Day for assistance with data collection, Dr Charlotte Apps for assistance with EMG analysis; Dr Ben Simpson and Dan Bigham for their insightful discussion about aerodynamics and cycling performance. Thanks also goes to Dr Katy Griggs for help with data collection and for proof reading the various iterations of this manuscript. We would also like to thank the participants who took part in the study, for giving up so much of their free time to assist with our work.

References

1. Martin JC, Gardner AS, Barras M, Martin DT. Modeling sprint cycling using field-derived parameters and forward integration. *Med Sci Sports Exerc*. 2006;38(3):592-597. doi:10.1249/01.mss.0000193560.34022.04
2. Froncioni A. Cycling Science. In: Cheung SS, Zabala M, eds. *Cycling Science: The Ultimate Nexus of Knowledge and Performance*. 1st ed. Champaign, IL: Human Kinetics; 2017:92-109.
3. di Prampero PE, Cortili G, Mognoni P, Saibene F. Equation of motion of a cyclist. *J Appl Physiol*. 2017;47(1):201-206. doi:10.1152/jappl.1979.47.1.201
4. Fintelman DM, Sterling M, Hemida H, Li F-X. The effect of time trial cycling position on physiological and aerodynamic variables. *J Sports Sci*. 2015;33(16):1730-1737. doi:10.1080/02640414.2015.1009936
5. Fintelman DM, Sterling M, Hemida H, Li FX. Optimal cycling time trial position models: Aerodynamics versus power output and metabolic energy. *J Biomech*. 2014;47(8):1894-1898. doi:10.1016/j.jbiomech.2014.02.029
6. Ashe MC, Scroop GC, Frisken PI, Amery CA, Wilkins MA, Khan KM. Body position affects performance in untrained cyclists. *Br J Sports Med*. 2003;37(5):441-444. doi:10.1136/bjsm.37.5.441
7. Kordi M, Fullerton C, Passfield L, Parker Simpson L. Influence of upright versus time trial cycling position on determination of critical power and W′ in trained cyclists. *Eur J Sport Sci*. 2019;19(2):192-198. doi:10.1080/17461391.2018.1495768
8. Verma R, Hansen EA, de Zee M, Madeleine P. Effect of seat positions on discomfort, muscle activation, pressure distribution and pedal force during cycling. *J Electromyogr Kinesiol*. 2016;27:78-86. doi:10.1016/j.jelekin.2016.02.003
9. Moura BM de, Moro VL, Rossato M, Lucas RD de, Diefenthaeler F. Effects of Saddle Height on Performance and Muscular Activity During the Wingate Test. *J Phys Educ*. 2017;28(1). doi:10.4025/jphyseduc.v28i1.2838
10. Fintelman DM, Sterling M, Hemida H, Li FX. Effect of different aerodynamic time trial cycling positions on muscle activation and crank torque. *Scand J Med Sci Sport*. 2016;26(5):528-534. doi:10.1111/sms.12479
11. Elmer SJ, Barratt PR, Korff T, Martin JC. Joint-specific power production during submaximal and maximal cycling. *Med Sci Sports Exerc*. 2011;43(10):1940-1947. doi:10.1249/MSS.0b013e31821b00c5

12. Bini RR, Daly L, Kingsley M, Daly L, Kingsley M. Muscle force adaptation to changes in upper body position during seated sprint cycling. *J Sports Sci*. 2019;37(19):2270-2278. doi:10.1080/02640414.2019.1627983

13. Dorel S, Couturier A, Hug F. Influence of different racing positions on mechanical and electromyographic patterns during pedalling. 2009:44-54. doi:10.1111/j.1600-0838.2007.00765.x

14. Nybo L. Cycling in the heat: performance perspectives and cerebral challenges. *Scand J Med Sci Sport*. 2010;20(SUPPL. 3):71-79. doi:10.1111/j.1600-0838.2010.01211.x

15. Galloway SDR, Maughan RJ, Laursen PB, et al. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med Sci Sport Exerc*. 1997;29(9):1240-1249. doi:10.1097/00005768-199709000-00018

16. Pauw K De, Roelands B, Geus B De, Meeusen R. Guidelines to classify subject groups in sport- science research. *Int J Sports Physiol Perform*. 2013;8:111-122. doi:10.1123/ijspp.8.2.111

17. Kyle C. The effects of crosswinds upon time trials. *Cycl Sci*. 1991;3:51-56.

18. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377-381.

19. ASHRAE. Thermal comfort. ASHRAE handbook of fundamentals. In: Atlanta, USA; 1997:8.1-8.26.

20. Griffiths ID, Boyce PR. Performance and Thermal Comfort. *Ergonomics*. 1971;14(4):457-468. doi:10.1080/00140137108931266

21. Faulkner SH, Hupperets M, Hodder SG, Havenith G. Conductive and evaporative precooling lowers mean skin temperature and improves time trial performance in the heat. *Scand J Med Sci Sports*. 2015;25 Suppl 1(S1):183-189. doi:10.1111/sms.12373

22. Cheuvront SN, Kenefick RW. CORP: Improving the status quo for measuring whole body sweat losses. *J Appl Physiol*. 2017;123(3):632-636. doi:10.1152/japplphysiol.00433.2017

23. ISO; International Organization for Standardization. *Ergonomics - Evaluation of Thermal Strain by Physiological Measurements*. Geneva: International Organization for Standardization; 2004.

24. Havenith G. Individualized model of human thermoregulation for the simulation of heat stress response. *J Appl Physiol*. 2001;90(5):1943-1954. doi:10.1152/jappl.2001.90.5.1943

25. Morris NB, Coombs G, Jay O. Ice slurry ingestion leads to a lower net heat loss during

exercise in the heat. *Med Sci Sports Exerc*. 2016;48(1):114-122. doi:10.1249/MSS.0000000000000746

26. DuBois D, DuBois EF. A formula to estimate the approximate surface area if height and weight be known. *Arch Intern Med*. 1916;17:863-871.

27. Parsons K. *Human Thermal Environments: The Effects of Hot, Moderate, Andcold Environments on Human Health,Comfort, and Performance, Third Edition.*; 2014. doi:10.1201/b16750

28. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1(1):50-57.

29. Wilson DG. *Bicycling Science*. 3rd ed. Cambridge, Massachusetts: The MIT Press; 2004.

30. Gnehm P, Reichenbach S, Altpeter E, Widmer H, Hoppeler H. Influence of different racing positions on metabolic cost in elite cyclists. *Med Sci Sports Exerc*. 1997;29(6):818-823. doi:10.1097/00005768-199706000-00013

31. Gagge AP, Herrington LP, Winslow CEA. Thermal Interchanges between the Human Body and its Atmospheric Environment. *Am J Hyg*. 1937;26:84-102.

32. Nielsen B. Olympics in Atlanta: A fight against physics. *Med Sci Sports Exerc*. 1996;28(6):665-668. doi:10.1097/00005768-199606000-00004

33. Ericson MO, Nisell R, Arborelius UP, Ekholm J. Muscular activity during ergometer cycling. *Scand J Rehabil Med*. 1985;17(2):53-61.

Table 1: Participant characteristics

Figure 1: A) power output at 4 mmol.L-1 when normalised to aerodynamic drag and frontal area ($W.CdA^{-1}$). B) The aerodynamic-physiological economy (APE) variation at different hip angles at 4 $mmol.L^{-1}$. † denotes a main effect of condition. *** = $P<0.005$ compared to control. Data presented as mean ± SD.

Figure 2: Time trial finish times at differing hip angles. Bars represent mean data and dots represent individual performances at each hip angle. Dots (•) represent individual rider finish times. Data presented as mean ± SD.

Figure 3: A) mean skin temperature, B) gastrointestinal temperature and C) the change in mean body temperature during each 25% of the target workload completed during the time trial. * denotes a main effect of time ($P<0.05$). Data presented as mean ±SD.

Figure 4: The change in power output, corresponding to a blood lactate concentration of 4 $mmol.L^{-1}$, compared to riders' control position at differing hip angles during the time trial. * denotes a main effect of hip angle, † denotes a difference compared to Δpower at 12˚ ($P<0.05$). Data presented as mean ±SD.

Figure 5: The association between hip angle during time trial cycling and A) metabolic energy expenditure and B) metabolic heat production. There we no post-hoc differences evident in panel B * denotes a main effect of hip angle,† denotes a difference between conditions ($P<0.05$). Data presented as mean ±SD.