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The Effect of Upper-Body Positioning on the Aerodynamic–Physiological Economy of Time-Trial Cycling

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Purpose: Cycling time trials (TTs) are characterized by riders' adopting aerodynamic positions to lessen the impact of aerodynamic drag on velocity. The optimal performance requirements for TTs likely exist on a continuum of rider aerodynamics versus physiological optimization, yet there is little empirical evidence to inform riders and coaches. The aim of the present study was to investigate the relationship between aerodynamic optimization, energy expenditure, heat production, and performance. ***Methods:*** Eleven trained cyclists completed 5 submaximal exercise tests followed by a TT. 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 with control occurred at 12° (−16 [20] W, $P = .03$; effect size [ES] = 0.8). There was a linear relationship between upper-body position and heat production ($R^2 = .414$, $P = .04$) 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] $\text{W}\cdot C_dA^{-1}\cdot\text{L}^{-1}\cdot\text{min}^{-1}$, ES = 0.4), and the lowest occurred at 24° (338 [28] $\text{W}\cdot C_dA^{-1}\cdot\text{L}^{-1}\cdot\text{min}^{-1}$, ES = 0.7), versus control (367 [41] $\text{W}\cdot C_dA^{-1}\cdot\text{L}^{-1}\cdot\text{min}^{-1}$). ***Conclusion:*** These data suggest that the physiological cost of reducing hip angle is outweighed by the aerodynamic benefit and that riders should favor aerodynamic optimization for shorter TT events. The impact on thermoregulation and performance in the field requires further investigation.

Keywords: aerodynamics, thermoregulation, electromyography, engineering

Cycling time trials (TTs) are characterized by riders' adopting optimal aerodynamic positions on the bike in order to lessen the impact of aerodynamic drag on their velocity. TT events can vary in both length and duration, ranging from a 4000-m individual pursuit completed in a velodrome lasting approximately 4 to 5 min, up to 100 miles or more on the road, lasting in excess of 4 to 5 h. It is likely that the optimal performance requirements for events of such divergent distances and durations exist on a continuum of ride aerodynamic versus physiological optimization.

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

$$F = 1/2\rho v^2 C_d A$$

where F is the total drag force (N), ρ is the density of air (1.2 $\text{kg}\cdot\text{m}^{-3}$ at sea level), v is the speed of the air relative to the rider and bike ($\text{m}\cdot\text{s}^{-2}$), C_d is the drag coefficient (dimensionless), and A is the frontal area (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 C_dA has become apparent, as 80% to 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 optimization, the physiological cost, and the overall performance outcome.

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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 favor 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 TT 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 due to an alteration in the length–tension relationship during the pedal cycle.[9] However, the data concerning this are equivocal.[8,12,13] Therefore, if the gain from optimizing aerodynamics does not outweigh the potential physiological cost of reducing hip angle, then TT performance will not improve. Moreover, given the relationship between speed and the power output required to overcome aerodynamic drag, shorter and faster events likely have a greater reliance on aerodynamic optimization, whereas longer duration TTs 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 TTs[15] or triathlon events. Currently, the exact balance between aerodynamic optimization 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 TT cycling. The primary aim of the present study was to investigate the relationship between hip angle, thermoregulation, economy, and performance. A secondary aim was to develop a unit of measurement that is sensitive to changes in rider position with respect to their aerodynamic and physiological economy. It was hypothesized that there would be a reduction in power output at the lactate threshold (LT) as the 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 TTs and/or triathlons for more than 5 y, volunteered to participate in this investigation (Table 1) and were equivalent to performance level 3.[16] All participants were free from injury and familiar with the type of testing involved.

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

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

Table 1 Participant Characteristics

Age, y	33 (9)
Weight, kg	78.0 (8.4)
Height, m	1.81 (0.06)
Body fat, %	12.2 (5.6)
$\dot{V}O_2$max, mL·kg^{-1}·min^{-1}	56.94 (6.95)
W_{max}, W	360 (40)
Power output at LT, W	283 (46)
Preferred hip angle, degrees	15 (3)
Range of preferred hip angle, degrees	9–19
A at preferred hip angle, m^2	0.353 (0.015)
C_d at preferred hip angle	0.629 (0.31)
C_dA, m^2	0.222 (0.018)

Abbreviations: A, frontal area; C_d, drag coefficient; C_dA, coefficient of aerodynamic drag per unit area; LT, 4 mmol·L^{-1} blood lactate threshold concentration. Note: Preferred hip angle relates to each rider's self-selected time-trial position as determined from his own bike geometry. All data are presented as mean (SD). N = 11.

Study Overview

The participants visited the laboratory on 7 separate occasions. The first visit involved the determination of each participant's TT 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. The riders' bikes were mounted on a stationary turbo trainer placed on a photographic green screen, with the stem positioned 2.2 m from a digital camera (Bioracer Aero; Bioracer Motion, Ravenshout, 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. The anthropometric data and the measured frontal area were then used to estimate each rider's coefficient of drag (C_d)[17]:

$$C_d = 4.45 \times (\text{Mass}^{-0.45})$$

and C_dA (Table 1):

$$C_dA = C_d \times A$$

The participants then performed an incremental $\dot{V}O_2$max test on a cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). The participants cycled at their preferred cadence, starting at 95 W, with a 35 W increase in power output every 3 min until volitional fatigue. $\dot{V}O_2$, $\dot{V}CO_2$, respiratory exchange ratio (RER), and heart rate were recorded continually throughout the test, with data averaged over the final 30 s of each stage.

The second visit acted as a familiarization to the TT protocol (see below) to minimize the potential learning effects on the performance measurements. The subsequent 5 visits consisted of a submaximal exercise test to a fixed LT of 4 mmol·L^{-1} 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 an alteration of handlebar height and reach. The participants were blinded to the conditions as far as practicable, and to minimize order effects, a balanced experimental order of the 5 conditions was used.

Experimental Protocol

An ingestible telemetric temperature pill (CoreTemp, HQ Inc, Palmetto, FL) was given to the participants to allow for the measurement of gastrointestinal temperature (T_{gi}), and it was swallowed 8 to 10 h prior to the start of all 5 of the main trials. Pill function was verified upon arrival at the lab using a receiver, and its position in the gastrointestinal tract was confirmed by the ingestion of water. Nude body weight was recorded (Adam Equipment Co Ltd, Milton Keynes, United Kingdom), and wireless thermistors (iButton, DS1922, Sunnyvale, CA) were secured to the skin. Muscle activity in the "rectus femoris," "biceps femoris," and "medial gastrocnemius" was recorded using wireless electromyography (EMG) sensors (2000 Hz; DataLite, Biometrics Ltd, Newport, United Kingdom). All participants were given a standardized triathlon suit (Huub, Derby, United Kingdom) in order to standardize the effect of textile insulation on skin and ensure comparable airflow effects due to the clothing.

Submaximal Exercise Test

The submaximal test followed the same procedure as described for the $\dot{V}O_2$max test; however, the test was terminated once the participant reached LT. Fingertip blood lactate samples were collected into 20-μL capillary tubes, at rest and during the last minute of each stage, and analyzed immediately (Biosen; EKF Diagnostics, Cardiff, United Kingdom). The rate of perceived exertion,[18] thermal comfort,[19] thermal sensation,[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 standardized 5-min active cooldown at 100 W.

Time Trial

Following a 30-min passive recovery, the participants performed a standardized 11-min warm-up prior to the TT (6 min at 50% W_{max}, 2 min at 60% W_{max}, 2 min at 70% W_{max}, and 1 min at 80% W_{max}). Following 5 min of rest, the riders began the TT. The participants were given a set amount of work, equivalent to cycling for 20 min 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 the participants cycled at their preferred cadence, as established from the $\dot{V}O_2$max test. The target workload was calculated as[21] follows:

$$\text{Target workload (kJ)} = \frac{(0.75 \times W_{max})}{1000} \times 1200$$

During the TT, the 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}, heart rate, cadence, rate of perceived exertion, thermal comfort, and thermal sensation were recorded. No specific performance feedback or encouragement was given during the TT. The participants could only view the 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 the fluid intake and sweat rate.[22] Throughout both the submaximal exercise test and the TT, mean wet globe bulb temperature was 18.6 (1.6)°C. Air flow was generated by a bank of 3 vertical fans at a velocity 2.5 m·s^{-1}.

Data Analysis

Aerodynamics

The C_d and A for each rider in their self-selected control position was calculated (see above). Given that C_d is difficult to measure in the absence of a wind tunnel and is largely determined by changes in overall rider profile, we estimated the riders' C_dA 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·C_dA^{-1} for each hip angle. In order to gain some insight into the combination of aerodynamic optimization and the potential physiological implications, W·C_dA^{-1} was normalized to the corresponding oxygen uptake at LT to quantify aerophysiological economy (APE; W·C_dA·L·min^{-1}).

Electromyography

A high-pass filter was applied to the raw EMG data at 50 Hz. 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. The 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 analyzed 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 8 locations (forehead, chest, scapula, upper arm, forearm, hand, thigh, and calf), with $\overline{T}_{sk}$ subsequently calculated.[23] The mean body temperature (T_b) was calculated as follows[24]:

$$T_b = (0.8 \times \text{mean}\, T_{gi}) + (0.2 \times \text{mean}\, T_{sk})$$

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

$$M = \dot{V}O_2 \times \frac{\left[\left(\frac{\text{RER}-0.7}{0.3}\right) \times e_c\right] + \left[\left(\frac{1.0-\text{RER}}{0.3}\right) \times e_f\right]}{60 \times \text{BSA}} \times 1000$$

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

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

Statistical Analysis

GraphPad Prism (version 8; San Diego, CA) software was used for all statistical analyses. The normal distribution of data was assessed by the Shapiro–Wilk test. Separate mixed methods analysis of variances were used to determine the main effects of hip angle and time. Where significant differences were identified, post hoc pairwise comparisons were conducted with a Bonferroni correction. One-way analysis of variances were used to determine the effect of the hip angle on TT 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 $P < .05$. All data are presented as mean (SD) unless otherwise stated. Magnitude-based inferences about the true (population) effect of hip angle on TT performance were calculated. The uncertainty in the effect was expressed as 90% confidence limits and as the likelihood that the true value of the effect represents substantial change: harm or benefit.[28] The smallest worthwhile change in TT performance was calculated using SD derived from the control trial data and multiplied by an effect size (ES) value of 0.2, which is equivalent to a small effect on performance. ESs corrected for bias using Hedge g were calculated as the ratio of the mean difference to the pooled SD of the difference, with 95% confidence intervals 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

There was a main effect of torso angle on C_dA ($P < .0001$). The control C_dA was 0.222 (0.018), with C_dA 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 the control ($P \le .01$) and each other ($P < .001$).

Aerodynamic–Physiological Economy

There was no effect of hip angle on W·C_dA^{-1} ($P = .418$, control = 1301 [253] W, 12° = 1270 [274] W, 16° = 1280 [296] W, 20° = 1266 [248] W, and 24° = 1247 [286] W; Figure 1A). When W·C_dA^{-1} was normalized 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 ($P < .0001$; Figure 1B), with a higher W·C_dA·L·min^{-1} value indicating higher aerophysiological efficiency (control = 367 [41] W·C_dA·L·min^{-1}; 12° = 384 [53] W·C_dA·L·min^{-1}, ES = 0.4; 16° = 367 [49] W·C_dA·L·min^{-1}, ES = 0.1; 20° = 361 [46] W·C_dA·L·min^{-1}, ES = 0.2; and 24° = 338 [28] W·C_dA·L·min^{-1}, ES = 0.7) However, post hoc comparisons only yielded a difference between the control and 24° ($P < .001$).

Performance Data—TT

There were no differences in TT finish time at any hip angle compared with the riders' control position (1108 [86] s, $P = .226$, Figure 2). However, there were small ESs present at 16° (1081 [101] s, ES = 0.3, –0.61 to 1.16, 2.2% faster than control) and 20° (1078 [73] s, ES = 0.3, –0.63 to 1.13, 1% faster than control) and a trivial effect at 12° (1121 [125] s, ES = 0.12, –0.99 to 0.76, 1.4% slower than control). The difference in finish time compared with control was 13 (81) s at 12°, –27 (48) s at 16°, –20 (46) s at 20°, and 0 (61) s at 24°. When considered relative to the smallest worthwhile change in performance, defined as being a change in performance of >1.5% or 17 s, qualitative inference indicates that the effect of a 12° hip angle was "possibly harmful" to performance (90% confidence limit, –0.12, –0.41 to 0.17), with the chances of a beneficial/trivial/harmful effect being 3.5%, 64.4%, and 32.1%, respectively. At 16°, the inference suggested that this was "possibly beneficial" to performance (0.3, –0.06 to 0.66), with the 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%, respectively.

There was a main effect of time on power output during the TT ($P = .003$), whereby power tended to decline throughout the TT. However, there was no effect of condition ($P = .152$) or an interaction ($P = .174$).

Performance Data—Thermometry

During the TT, there was a main effect of time on $\overline{T}_{sk}$ ($P < .0001$, Figure 3A) but no effect of condition ($P = .149$) or interaction ($P = .243$). A similar effect was evident for T_{gi} with a main effect of time only ($P < .0001$, Figure 3B). Consequently, the mean T_b reflected these data and showed a main effect of time only ($P < .0001$, Figure 3C).

Performance Data—Submaximal Test

There were no differences in power output at a blood lactate concentration of 4 mmol·L^{-1} (control = 286 [42] W, 12° = 271 [49] W, 16° = 283 [52] W, 20° = 286 [43] W, and 24° = 284 [62] W, $P = .222$). However, there was a moderate effect at 12° compared with the 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·L^{-1} compared with the control ($P = .045$, Figure 4). There were larger reductions in power output compared with the control evident between 12° (–16 [20] W) compared with the change at 20° (–1 [19] W, both Ps = .026) and 24° (2 [17] W, $P = .009$, Figure 4).

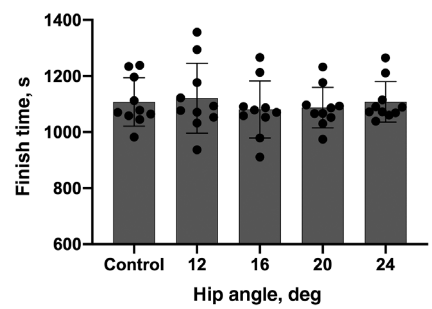

Figure 2 — Time trial finish times at differing hip angles. Bars represent mean data, and dots represent individual performances at each hip angle. Dots (•) represent individual rider finish times. Data are presented as mean (SD).

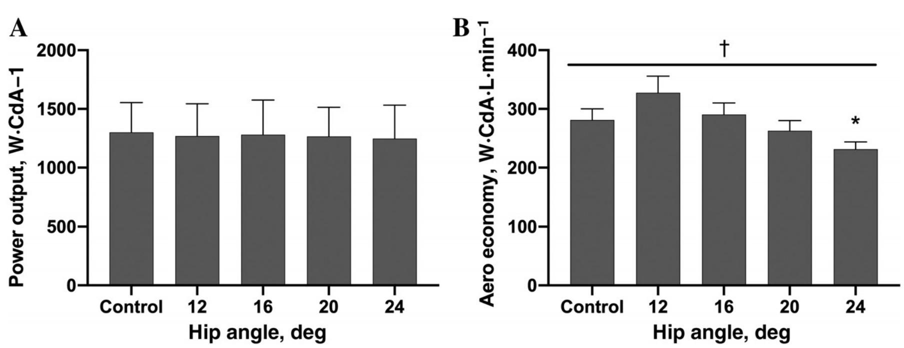

Figure 1 — (A) Power output at 4 mmol·L^{-1} when normalized to aerodynamic drag and frontal area (W·C_dA^{-1}). (B) The aerodynamic–physiological economy variation at different hip angles at 4 mmol·L^{-1}. †A main effect of condition. *$P < .005$ compared with control. Data are presented as mean (SD).

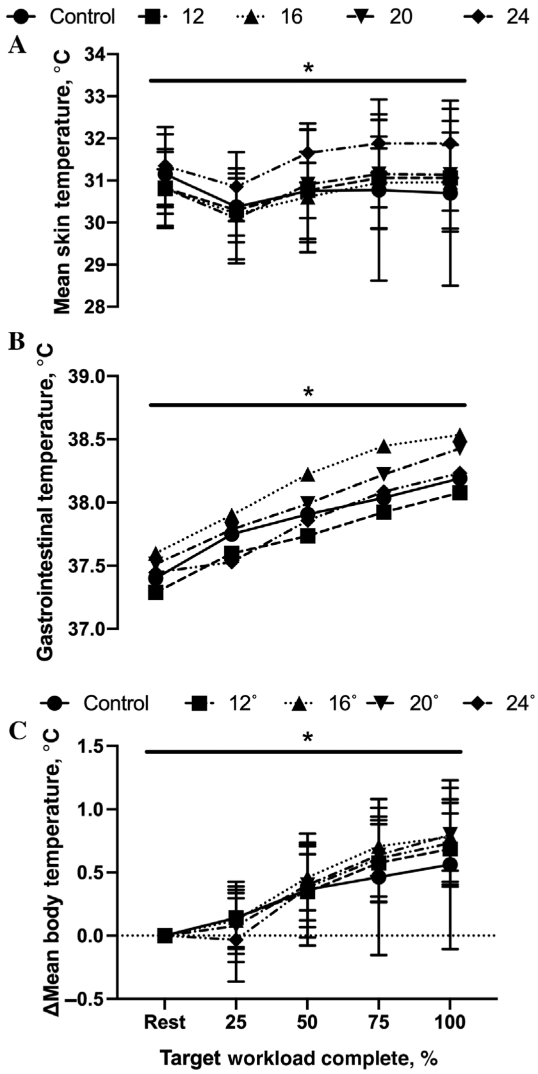

Figure 3 — (A) Mean skin temperature, (B) gastrointestinal temperature, and (C) the change in mean body temperature during each 25% of the target workload completed during the time trial. *A main effect of time ($P < .05$). Data are presented as mean (SD).

Energy Expenditure, Heat Production, Economy, and Efficiency

There was an effect of hip angle on metabolic energy expenditure ($P = .044$), with differences between the control (1222 [167] W) and 12° (1150 [166] W, $P = .048$, ES = 1.74, Figure 5A). There was an overall effect of hip angle on $\dot{H}_{\text{prod}}$ ($P = .038$, Figure 5B), which increased linearly with the hip angle ($R^2 = .414$, $P = .037$). However, there were no clear differences between conditions. Compared with the control (936 [133] W), the ESs of the hip angle on $\dot{H}_{\text{prod}}$ ranged from trivial at 20° (934 [119] W, ES = 0.1), small at 16° (928 [147] W, $P = .808$, ES = 0.2) to large at 12° (880 [125] W, $P = .077$, ES = 1.5) and 24° (983 [196] W, ES = 1.4).

There was no effect of hip angle on cycling economy ($P = .22$), although there was a small effect evident at 24° (77.9 [5.3] W·L·min^{-1}) compared with the control (81.5 [5.5] 2 W·L·min^{-1}, $P = .041$, ES = 0.5). Similarly, there was no effect of hip angle on efficiency ($P = .161$), although there was a moderate effect evident at 24° (21.8 [1.5]%) compared with the control (22.7 [1.8]%, $P = .078$, ES = 0.6).

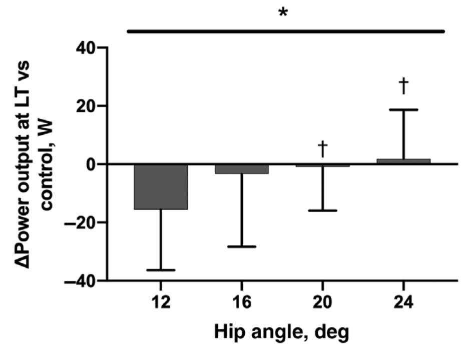

Figure 4 — The change in power output, corresponding to a blood lactate concentration of 4 mmol·L^{-1}, compared with riders' control position at differing hip angles during the time trial. *A main effect of hip angle. †A difference compared with Δpower at 12° ($P < .05$). Data are presented as mean (SD).

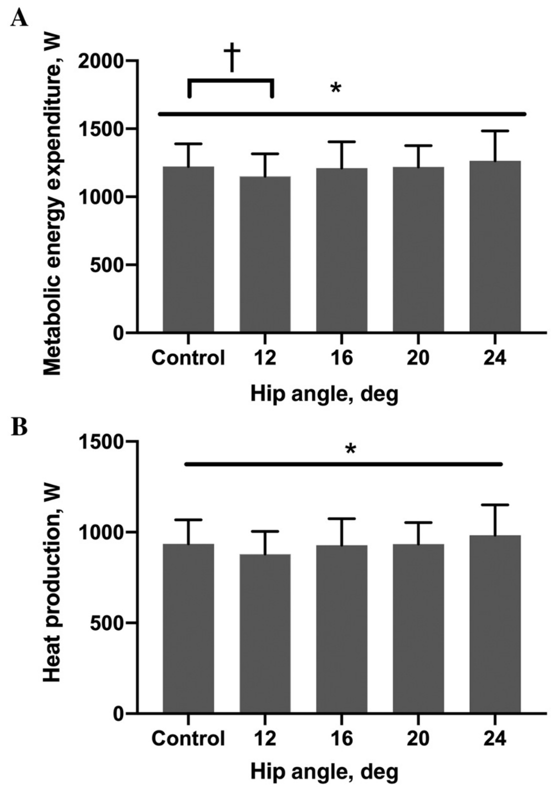

Figure 5 — The association between hip angle during time trial cycling and (A) metabolic energy expenditure and (B) metabolic heat production. There were no post hoc differences evident in (B). *A main effect of hip angle. †A difference between conditions ($P < .05$). Data are presented as mean (SD).

Electromyography

Compared with the control, there were no differences in the relative muscle activation of the quadriceps ($P = .517$), hamstrings ($P = .193$), or gastrocnemius ($P = .170$) at a power output equivalent to a blood lactate concentration of 4 mmol·L^{-1}. There were no main effects of hip angle on summative muscle activation for either relative ($P = .232$) or absolute ($P = .410$) 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 TT performance. The main finding is that, with increasing hip angle (ie, 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 the lower hip angles is overcome by a reduction in aerodynamic drag and improved APE. Practically, these data show that, for short-duration TTs (<~20 min), riders should favor optimizing 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 (C_d, dimensionless). A typical cyclist may have a C_d of approximately 1.2 when sitting and 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 optimized TT position.[29] Importantly, C_d is influenced by the frontal area of an object (A, m^2). Therefore, if you have 2 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, a lower C_d per unit of frontal area (C_dA, m^2). Consequently, a reduction in hip angle, and therefore frontal area, should lower C_dA, making a rider more aerodynamic, due 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 cannot generate sufficient power to increase the speed of travel due to a biomechanical disadvantage, then the balance in positional optimization 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 normalized to C_dA ($\text{W}\cdot C_dA^{-1}$), where a higher sustainable $\text{W}\cdot C_dA^{-1}$ value is considered more desirable.

From the power data obtained at 4 mmol·L^{-1}, a hip angle of approximately 16° appears to be 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·L^{-1} compared with more open hip angles. This may result in improved TT performance in competition, where aerodynamic drag is a significant issue. This is supported by our calculations aimed at estimating the APE of cycling, which demonstrate that overall efficiency may in fact be increased at a reduced hip angle, where aerodynamic drag is minimized. 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 ($\text{W}\cdot C_dA\cdot\text{L}\cdot\text{min}^{-1}$) 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 TT efforts (~80%–85% W_{max}). Further work should be conducted to establish the relationship between aerodynamic optimization 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 the hip angle increased, there was no subsequent difference in the 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 the 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 $\overline{T}_b$ between conditions. As no change in the sweat rate was reported between trials, the primary mechanism increasing heat loss must be a consequence of the 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 TTs 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 position during the ride, while having a minimal effect on the 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 setup 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 hypothesized 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 the power output at 4 mmol·L^{-1} did not differ between conditions. One possible explanation is that the activity in other muscle groups was altered as a consequence of changes to the 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 occur 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 recorded EMG in 3 individual muscles in the lower limb, and it has been shown that lower limb EMG is sensitive to change in at least 8 individual muscles.[33] This raises the possibility that muscle activity was altered in muscles other than those that were measured, which may explain the reported increase in M and $\dot{H}_{\text{prod}}$.

Practical Application

The application of these data relates to the riders' position selection for TT events. Our data show that a focus on aerodynamic optimization outweighs the physiological cost of reducing hip angle on power output at LT. Importantly, the use of APE, as a measure of overall efficiency, provides athletes and coaches with a direct way of assessing the optimal TT position for a cyclist. Further work is needed to understand the relationship between TT position, $\dot{H}_{\text{prod}}$, and heat storage in order to determine the thermal effects of position that may affect performance in long duration TTs, 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 the riders' C_dA, we show that there is a clear trade-off between metabolic efficiency and aerodynamic optimization and suggest that the APE index may quantify this relationship. The reduction in power at lower hip angles is overcome by lower aerodynamic drag and improved APE. Furthermore, these data show that a rider's position during a TT may influence $\dot{H}_{\text{prod}}$. 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 TTs (<~20 min), riders should favor optimizing 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.

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