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Improving Cycling Performance

How Should We Spend Our Time and Money

Asker E. Jeukendrup[1] and *James Martin*[2]

1 Human Performance Laboratory, School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, England

2 Department of Exercise and Sport Science, University of Utah, Salt Lake City, Utah, USA

Contents

Abstract

Cycling performance is dependent on physiological factors which influence mechanical power production and mechanical and environmental factors that affect power demand. The purpose of this review was to summarize these factors and to rank them in order of importance. We used a model by Martin et al. to express all performance changes as changes in 40km time trial performance. We modelled the performance of riders with different ability ranging from novice to elite cyclists. Training is a first and most obvious way to improve power production and was predicted to have the potential to improve 40km time trial performance by 1 to 10% (1 to 7 minutes). The model also predicts that altitude training *per se* can cause a further improvement of 23 to 34 seconds. Carbohydrate-electrolyte

drinks may decrease 40km time by 32 to 42 seconds. Relatively low doses of caffeine may improve 40km time trial performance by 55 to 84 seconds.

Another way of improving time trial performance is by reducing the power demand of riding at a certain velocity. Riding with hands on the brake hoods would improve aerodynamics and increase performance time by ≈5 to 7 minutes and riding with hands on the handlebar drops would increase performance time by 2 to 3 minutes compared with a baseline position (elbows on time trail handle bars). Conversely, riding with a carefully optimised position could decrease performance time by 2 to 2.5 minutes. An aerodynamic frame saved the modelled riders 1:17 to 1:44 min:sec. Furthermore, compared with a conventional wheel set, an aerodynamic wheel set may improve time trial performance time by 60 to 82 seconds.

From the analysis in this article it becomes clear that novice cyclists can benefit more from the suggested alterations in position, equipment, nutrition and training compared with elite cyclists. Training seems to be the most important factor, but sometimes large improvements can be made by relatively small changes in body position. More expensive options of performance improvement include altitude training and modifications of equipment (light and aerodynamic bicycle and wheels). Depending on the availability of time and financial resources cyclists have to make decisions about how to achieve their performance improvements. The data presented here may provide a guideline to help make such decisions.

A variety of internal and external factors interact to determine cycling velocity (table I). Chief among those are physiological factors which influence mechanical power production (internal factors), and mechanical and environmental factors that affect power demand (external factors). Although these factors always influence cycling performance, they most obviously affect time trial performance in which race tactics are less important. Most of these factors have been discussed in detail in the articles that proceed this review.[1,4,10,19,20] The purpose of this review is to summarise these findings and to rank them in order of importance. In other words, we sought to determine where and how we should spend our time or money to improve cycling performance. For example, is it more effective to buy aerodynamic wheels or should we invest in altitude training?

Clearly, the relative importance of factors as diverse as interval training, carbohydrate feeding and aerodynamic bicycle components cannot be directly ranked. Rather, some common measure that allows indirect comparison of the relative importance of each factor must be used. In the present review, we used a mathematical model[18] to facilitate comparison of physiological, mechanical and environmental factors that affect cycling performance. Studies on the physiological aspects of cycling performance (e.g. interval training) were used to estimate how each factor would influence the power a cyclist could sustain for a 40km time trial. The model was then used to predict the effects of those power changes on 40km time trial performance. In this way, the effects of internal and external factors were com-

Table I. Factors that can influence cycling performance

Internal factors
Training[1-3]
Altitude training[4-8]
Carbohydrate[9-10]
Caffeine[11-15]
External factors
Bodyweight[9,16,17]
Body position[18,19]
Clothing[18,19]
Bicycle[18,19]
Wheels[18,19]

pared with respect to their influence on the time to complete a 40km time trial.

1. The Model

Cycling velocity results from the dynamic equilibrium between power production and power demand. The mathematical model used in this review was reported by Martin et al.[18] and included terms for mechanical power produced by the cyclist and for all the relevant external factors including: aerodynamic drag, wind conditions, rolling resistance, bearing friction, potential and kinetic energy, and mechanical efficiency. The expression for total power delivered to the bicycle cranks was:

$$P_{TOT} = \{V_a{}^2 V_G \tfrac{1}{2}\rho(C_DA + F_w) + V_G C_{RR} m_T g \mathrm{Cos}[\mathrm{Tan}^{-1}(G_R)] + V_G(91 + 8.7V_G) \times 10^{-3} + V_G m_T g \mathrm{Sin}[\mathrm{Tan}^{-1}(G_R)] + \tfrac{1}{2}(m_T + I/r^2)(v_f{}^2 - v_i{}^2)/(t_i - t_f)\}/E_C$$

where: V_a is the air velocity of the bicycle tangent to the direction of travel of the bike and rider (which is dependent on wind velocity and the ground velocity of the bicycle); V_G is the ground velocity of the bicycle; ρ is air density; C_D is the coefficient of drag of the bicycle and rider; A is the frontal area of the bicycle and rider; F_w is an expression equivalent to the drag area (C_DA) of the spokes; C_{RR} is the coefficient of rolling resistance; m_T is the total mass of the bicycle and rider; g is the acceleration due to gravity; G_R is the gradient of the road surface; $V_G(91 + 8.7V_G) \times 10^{-3}$ is an expression for wheel bearing friction; I is the combined moment of inertia of 2 wheels; and r is the radius of the bicycle wheel. Subscripts i and f represent initial and final conditions over some interval. E_C is the efficiency of the chain drive system.

Martin et al.[18] validated this model by comparing predicted power with power measured during outdoor road cycling and reported that modelled power agreed with the measured power [modelled power = 1.00 × measured power; coefficient of determination (R^2) = 0.97, standard error of the estimate (SEE) = 2.7W]. Thus, we are confident that this model will serve as a valid tool for comparing the effects of various internal and external factors.

2. Methods of Comparison

The effects of several physiological factors were compared within the context of a novice cyclist with a relatively short history of cycling training [maximal oxygen uptake ($\dot{V}O_{2max}$) 48 ml/kg/min with a lactate threshold of 65% $\dot{V}O_{2max}$], a well-trained cyclist ($\dot{V}O_{2max}$ 66 ml/kg/min with a lactate threshold of 75% $\dot{V}O_{2max}$) and an elite road cyclist ($\dot{V}O_{2max}$ 80 ml/kg/min with a lactate threshold of 80% $\dot{V}O_{2max}$). The mass of all 3 simulated riders was 70kg and air density was assumed to be 1.2 kg/m^3. For the evaluation of internal factors, the drag area of the simulated riders was assumed to be 0.269m^2.[18] The model was used to simulate performance on a 40km course in which the rider would travel 5km up a 1% grade into a 2 m/sec headwind, 5km down a 1% grade into a 2 m/sec headwind, 5km up a 1% grade with a 2 m/sec tailwind and 5km down a 1% grade with a 2 m/sec tailwind, 10km along a flat into a 2 m/sec headwind and 10km along a flat with a 2 m/sec tailwind. For the specified model parameters, the baseline performance times for the 40km time trial were: 72:56 (min:sec), 58:35 and 52:02 for the modelled novice, trained and elite cyclists, respectively. These values will be used to compare the effects of various internal and external factors.

3. Internal Factors

3.1 Training

Training is recognised as one of the main modifiers of exercise performance. Numerous previous investigators have described the performance benefits of training and the underlying mechanisms. Participants in most of these studies, however, were untrained individuals or patients and little or no information is available on the effect of additional or alternative training in already well trained individuals such as elite cyclists.[1]

Early reports showed that untrained individuals can increase their $\dot{V}O_{2max}$ by 20 to 38% after 9 to 12 weeks of training[21-24] (table II). The very large increases in $\dot{V}O_{2max}$ were observed in the elderly, whereas younger people showed somewhat

Table II. Summary of representative studies showing the effects of several weeks of training on performance indices in untrained, moderately trained and well-trained cyclists

Participants	$\dot{V}O_{2max}$ (ml/kg/min)	Training	Performance improvement (%)			Reference
			W_{max}	$\dot{V}O_{2max}$	40km time	
Untrained individuals						
Young and old men (untrained)		12 weeks	NA	28-38	NA	24
12 untrained individuals		10 weeks 40 min/day, 6 days/week	NA	25	NA	23
13 untrained individuals	42.3	10 weeks 40 min/day, 6 days/week	NA	10-20	NA	22
9 untrained individuals		9 weeks 40 min/day, 6 days/week	NA	23	NA	21
Moderately trained individuals						
16 moderately trained cyclists	56.8	4 weeks of mixed training	NA	5.5	6.8	25
		8 weeks of mixed training	NA	7.0	8.4	
Well-trained individuals						
4 trained cyclists *vs* 4 controls	61.3	3 weeks with 6 HIT sessions (8×4 min 85% W_{max} with 1.5 min recovery)	2.4	NA	2.3	3
8 trained cyclists	≈64	6 weeks, 15% of normal training replaced by HIT	5.0	NA	2.4	26
12 trained cyclists	65.7	4 weeks, 15% of normal training replaced by HIT	4.3	NA	3.5	2

HIT = high intensity training; **NA** = not applicable; $\dot{V}O_{2max}$ = maximal oxygen uptake; W_{max} = peak power.

smaller improvements. This may be related to the low initial $\dot{V}O_{2max}$. Generally, a low $\dot{V}O_{2max}$ at the onset of training will result in large improvements after training whereas high initial $\dot{V}O_{2max}$ values result in smaller increases. Unfortunately, $\dot{V}O_{2max}$ is not always a good indicator of exercise performance and therefore it is difficult to predict performance improvements from these studies. However, it is likely that these training programmes resulted not only in an increased $\dot{V}O_{2max}$ but also in a significant shift of the lactate threshold. In the model we have therefore used the changes in $\dot{V}O_{2max}$ as a reflection of changes in 40km time trial performance.

Several studies have been conducted in moderately trained to trained athletes. Norris and Petersen[25] investigated the effect of an 8-week training programme (5 times per week, 40 to 55 minutes) on the performance of 16 competitive cyclists ($\dot{V}O_{2max}$ 57 ml/kg/min). Performance was evaluated with a $\dot{V}O_{2max}$ test and a simulated 40km time trial after 4 and 8 weeks. Performance improvements were observed within 4 weeks and by the end of the 8 weeks of training $\dot{V}O_{2max}$ was improved by 5% and the 40km time was reduced by 8.4%. These large changes are likely to be related to the low starting level of the cyclists (i.e. the study was performed at the beginning of the season).

Westgarth-Taylor et al.[26] investigated the effects of a modified training regimen in 8 cyclists ($\dot{V}O_{2max}$ ≈64 ml/kg/min). A total of 15% of their endurance training was replaced by high intensity training. After 6 weeks peak power (W_{max}) was increased from 404 ± 40W to 424 ± 53W (5.0%) and time to complete 40km was 2.4% less. During the time trial cyclists averaged 327 ± 51W after training compared with 291 ± 43W before (11.3%). They not only performed at a higher absolute workload but also at a higher relative intensity (78.1 *vs* 72.6% W_{max}), possibly indicating a shift in lactate threshold. Similar results were obtained by the same research group when participants trained in a similar manner for 4 weeks.[2] W_{max} was increased 4.3% and the 40km time was improved by 3.5% (see table II).

Stepto et al.[3] studied the effects of 5 different interval training protocols in 20 trained cyclists ($\dot{V}O_{2max}$ 61.3 ml/kg/min). Cyclists completed 6 interval sessions in 3 weeks, and before and after the training period W_{max} and 40km time trial performance were measured. The interval training protocols ranged from 12 times 30 seconds at 175% W_{max} to 4 times 8 minutes at 80% W_{max}. Interestingly, the most profound changes in performance (2.4% increase in W_{max} and 2.3% improvement in 40km time trial performance; table II) were observed with a protocol consisting of 8 times 4 minutes at 85% W_{max} interspersed with a 1.5 minute rest.

Although little or no data are available on the effects of training in already highly trained cyclists,[27] anecdotal evidence suggests that improvements in performance are only small despite significant increases in training volume and intensity. In World Class cyclists in the competitive season, these improvements in 40km time trial performance are likely to be in the range of 1 to 3% (unpublished observations). However, it must be noted that much larger improvements can be observed in the beginning of the season when these cyclists are relatively untrained.

In summary, in novice cyclists, a training programme which includes high-intensity intervals and sustained endurance effort can increase performance by 5 to 10%. The effects of modified training on 40km time trial performance in already well-trained individuals have only been reported to be 2 to 4%. It is likely that the margins for improvement are smaller in elite cyclists (1 to 3%). With the model presented above, these changes have been translated into 40km times in table III.

3.2 Altitude Training

The effects of altitude training have been discussed extensively by Hahn and Gore[4] and elsewhere.[5-8] Generally, it is thought that living and training at moderate altitude has little or no effect on performance at sea level.[4] However, there is some evidence that living high and training low might have positive effects.[5,8,28,29] In runners, 5km running performance improved by 2.2% and $\dot{V}O_{2max}$ by 3.9% when they lived at 2500m and trained at 1250m.[29] In a follow-up study by the same research group[30] in highly trained athletes ($\dot{V}O_{2max}$ 72 ml/kg/min), $\dot{V}O_{2max}$ and 3km run time improved by 1.1 and 2.2%, respectively. Unfortunately, this study had no control group.

Most of the studies have been performed in runners and very little information is available on cyclists.[31] Furthermore, performance measurements have typically been of short duration from seconds up to ≈20 minutes, and therefore extrapolation to 40km time trial performance is difficult. Nevertheless, as concluded by Hahn and Gore[4] performance improvements as a result of altitude training appear to be very small (0 to 2%). Whether these improvements can be extrapolated to cyclists has not been demonstrated. Even so, it seems reasonable to assume that the improvements observed in runners are similar to those in cyclists. Therefore, we have estimated that altitude training may elicit a 2% increase in performance power. With that improvement, the model predicts a decrease in time trial performance time of 34 seconds for the novice cyclist (72:22 *vs* 72:56), 26 seconds for the trained

Table III. The effects of several weeks of training on 40km time in novice, trained and elite cyclists. Performance time data are presented as min:sec

	40km time before training	Effect after training		
		minimum	maximum	average
Novice	72:56	69:21	65:38	67:29
		–3:35	–7:18	–5:27
Trained	58:35	57:25	56:15	56:50
		–1:10	–2:20	–1:45
Elite	52:02	51:30	50:29	51:00
		–0:32	–1:33	–1:02

cyclist (58:09 *vs* 58:35) and 23 seconds for the elite cyclist (51:39 *vs* 52:02).

3.3 Nutrition

3.3.1 Carbohydrate-Electrolyte Solutions

As reported elsewhere,[10] the effects of many nutritional supplements on endurance performance have been previously investigated.

Results from several well controlled investigations[32-34] suggest that ingestion of water and carbohydrate improves exercise performance. Jeukendrup et al.[33] reported that power produced by well trained cyclists during a simulated 40km time trial performance was improved by 2.3% (297.5 ± 10.3W) by ingestion of a water and carbohydrate beverage compared with a placebo (291.0 ± 10.3W). Similarly, el-Sayed et al.[34] reported that ingestion of an 8% carbohydrate solution improved power produced by trained cyclists during a 1-hour 'all-out' cycling trial by 3.0% (277 ± 3W) compared with placebo (269 ± 3W). Using a slightly different protocol, Below et al.[32] showed that carbohydrate feeding improved power output by 12% during a 10 minutes all-out exercise bout after 50 minutes of constant load cycling. This finding may be particularly relevant to road racing in which performance during the final kilometres may determine success or failure. With regard to time trial performance, those results suggest that average power over a 1-hour period would be increased by at least 2%.

Taken together these results suggest that ingestion of fluid and carbohydrate may increase 40km time trial performance power by 2 to 3%. Accordingly, we have used our model to predict the effect of a 3% change in power on time to complete a 40km time trial. The model predicts that a 3% increase in power would decrease 40km time by 42 seconds for the novice cyclist (72:14 *vs* 72:56), 36 seconds for the well-trained cyclist (57:59 *vs* 58:35) and 32 seconds for the elite cyclist (51:30 *vs* 52:02). Even though the total increase in power is less for the novice cyclist (6 *vs* 9 and 12W), the decrease in 40km time is greater.

3.3.2 Caffeine

Caffeine is usually classified as a nutrient but when used in large doses may have pharmacological effects. Caffeine is banned by the International Olympic Committee, but only when concentration in the urine exceeds 12 mg/L. Concentrations below that threshold are considered allowable.

Several investigators have reported caffeine to improve exercise capacity (time to exhaustion) or performance (time to complete a certain amount of work).[11-15] However, to our knowledge, there is only one study of the effects of caffeine ingestion on 40km time trial performance. Kovacs et al.[14] investigated the effects of ingesting different levels of caffeine in combination with a carbohydrate-electrolyte drink on performance in 15 trained cyclists (≈67 ml/kg/min). The best performances were observed with the highest caffeine doses (225 and 320mg) and individuals produced 308 ± 9 and 309 ± 10W, respectively, in these trials compared with 295 ± 9W in the control trial; a 5% increase in power. It is important to note that the dose of caffeine used in this study was small and did not result in high caffeine concentrations in the urine (below 5 mg/L). Pasman et al.[13] also showed large improvements in time to exhaustion at 80% $\dot{V}O_{2max}$ with a relatively low dose of caffeine (5 mg/kg).

The fact that large effects on endurance capacity were observed over a fairly large range of aerobic fitness levels suggests that caffeine has similar effects in relatively untrained cyclists and elite cyclists.[11-15] Therefore, caffeine ingestion was assumed to increase power by 5% for all 3 of our modelled participants. That 5% increase in power resulted in a time savings of 84 seconds for the novice cyclist (71:32 *vs* 72:56), 63 seconds for the trained cyclist (57:32 *vs* 58:35) and 55 seconds for the elite cyclist (51:07 *vs* 52:02).

4. External Factors

4.1 Body and Bicycle Mass

4.1.1 Bicycle Mass

The baseline parameters used in our model included a bicycle mass of 10kg. Much lighter equipment is available and, therefore, we have used our

Table IV. The effects of road grade (3 to 12%) and bicycle weight (standard or light) on the time to ride 20km uphill. Performance time data are presented as min:sec

	3% grade		6% grade		12% grade	
	standard	light	standard	light	standard	light
Novice	63:48	62:14	106:48	103:10	202:25	195:00
		–1:34		–3:38		–7:25
Trained	42:37	41:53	63:48	61:56	115:33	111:31
		–0:42		–1:52		–4:02
Elite	35:01	34:32	48:56	47:41	84:47	81:59
		–0:29		–1:15		–2:48

model to estimate the effect of a 7kg bicycle on 40km time trial performance time. Compared with the 10kg bicycle used in our baseline calculations, the lighter bicycle would decrease 40km time trial performance time by 13 seconds for the novice cyclist (72:43 *vs* 72:56), 7 seconds for the trained cyclist (58:28 *vs* 58:35) and 5 seconds for the elite cyclist (51:57 *vs* 52:02).

4.1.2 Body Mass

To accurately assess the effects of increases or decreases of body mass on cycling performance, both the mass and the resulting change in body surface area must be accounted for in the model parameters. Specifically, any change in body mass is likely to be accompanied by a change in body surface area and, therefore, a change in drag area. In this analysis, drag area was adjusted by the ratio of the decreased mass to the baseline mass raised to the power of 0.425.[20] Thus, a decrease of 3kg would decrease drag area by 1.84% to 0.264m^2. Using this joint decrease in body mass and drag area the model predicted a decrease in 40km time of 25 seconds for the novice cyclist (72:31 *vs* 72:56), 21 seconds for the trained cyclist (58:14 *vs* 58:35) and 19 seconds for the elite cyclist (51:43 *vs* 52:02).

4.1.3 Effects of Mass on Climbing

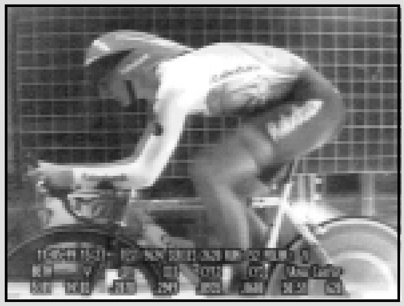
The predicted effects of changes in bicycle and body mass on 40km time trial performance presented in sections 4.1.1 and 4.1.2 seem quite low (25 seconds or less). This small effect was due, in part, to the profile of the modelled course, but also to the fact that any additional weight provided additional propulsive force on the descent portion of the course. However, in certain situations the advantage of additional weight during the descent will be nullified by other factors. For example, if the cyclist must use braking to negotiate the descent, that advantage is greatly reduced. Similarly, in a mass start race, if a rider does not maintain contact during a climb, he or she may be unable to regain contact with the group during the descent because the group may descend faster than the individual. Therefore, we have performed additional analyses to estimate the effects of a decrease of 3kg to bicycle mass for 20km climbs of 3, 6 and 12% grade. These model conditions were intended to simulate the effects of mass on a course in which the speed for the descent was limited by handling concerns rather than power. As shown in table IV, the model predicts that the use of a 7kg bicycle will decrease the time required for a 20km climb by 29 seconds to over 7 minutes. The novice cyclist will benefit the most from reduced mass but the effect on elite performance (almost 3 minutes) is dramatic as well. Indeed, a savings of 3 minutes would almost certainly have a significant effect on the outcome of a professional road or stage race.

4.2 Aerodynamics

4.2.1 Body Position

The effects of body position on time trial performance were analysed in 4 typical positions: a rider with his hands on the brake hoods (drag area of 0.358m^2), a rider with his hands on the drops of road handle bars (0.307m^2), a rider with his elbows on time trial handle bars (0.269m^2; baseline condition) and a rider with a wind-tunnel optimised po-

Drag area (m²)	0.259
Estimated power 40km (W)	372
Weight of bicycle plus rider (kg)	80
Aero front wheel	
Disc rear wheel	
Estimated time 40km (min:sec)	52:22
Average speed (km/h)	45.83



Drag area (m²)	0.244
Estimated power 40km (W)	372
Weight of bicycle plus rider (kg)	80
Aero front wheel	
Disc rear wheel	
Estimated time 40km (min:sec)	51:22
Average speed (km/h)	46.72

Fig. 1. Example of a wind tunnel experiment and the theoretical advantage of a change in position on 40km time trial performance. In this procedure, the cyclist's handlebars were lowered 18mm, elbow pads were moved backward 190mm, and hands were moved upward (≈6cm). Wind resistance was measured at angles ranging from 0 to 15°. This relatively small change in position is unlikely to compromise power production but resulted in a 5.9% reduction in drag area from 0.259 to 0.244m^2. This decrease in drag area should result in a 60-second improvement in 40km time for this cyclist (from Rabobank Professional Cycling Team with permission).

sition (0.240m^2) [personal communication, John E. Cobb] (fig. 1).

The effects of these 4 positions on time trial performance of our 3 modelled participants are shown in table V. Riding with hands on the brake hoods would increase performance time by approximately 5 to 7 minutes and riding with hands on the handlebar drops would increase performance time by 2 to 3 minutes compared with our baseline position. Conversely, riding with a carefully optimised position could decrease performance time by 2 to 2.5 minutes.

4.2.2 Bicycle Frame

The effect of using an aerodynamic time trial bicycle frame compared with a regular (round steel tube) frame was evaluated for each simulated rider. The aerodynamic frame (e.g. Cervelo or Lotus) was assumed to have 0.02m^2 less drag area than the regular frame but the rider's body was assumed to remain in the standard position. Thus, the total drag area for the aerodynamic bicycle and rider was assumed to be 0.249m^2. With this drag area, our model predicted a 40km time trial time of 71:12 for the novice cyclist, 57:09 for the trained cyclist and 50:45 for the elite cyclist; the aerodynamic frame saved the modelled riders 1:44, 1:26 and 1:17, respectively.

4.2.3 Frame and Body Position Combined

If the effects of bicycle and body drag area are additive (i.e. if the bicycle and the rider occupy different portions of the frontal area), then total drag area may be dramatically decreased by using an aerodynamic frame and an optimised rider position. Based on the drag area values presented above, drag area could be reduced to ≈0.22m^2. If such a drag area were achieved, time trial performance time would be decreased to 68:33, 54:57 and 48:47, for the novice, trained and elite cyclist, respectively; a time savings of 4:24, 3:38 and 3:15, for our modelled riders compared with performance with a standard frame and position. Indeed, such a low drag area may be exactly what is achieved by the World's top time trial riders today.

4.2.4 Wheels

The baseline parameters of our model assumed the use of aerodynamic wheels. Therefore, to assess the effects of aerodynamic wheels we determined the increase in 40km time trial performance time that would result when total drag area was increased by using a conventional wheel set with 36 round wire spokes. The drag area of these standard wheels has been reported to be ≈0.0042m^2 greater than that of the best aerodynamic wheels.[35] To realistically model the effects of 2 wheels, we assumed that the rear wheel was partially shielded by the bicycle frame such that the total drag area of the bicycle equipped with standard wheels was 0.0063m^2 greater than that for the aerodynamic wheel set (i.e. 1.5 times the increase associated with one wheel). Compared with the aerodynamic wheel set, the conventional wheel set increased time trial performance time by 82 seconds for the novice cyclist (74:18 *vs* 72:56), 67 seconds for the trained cyclist (59:42 *vs* 58:35) and 60 seconds for the elite cyclist (53:02 *vs* 52:02).

4.2.5 Wheel Choice: Weight Versus Aerodynamics

When selecting a wheel set for a specific competition, cyclists often must choose between a light nonaerodynamic wheel and a heavier more aerodynamic wheel. This decision may be particularly important when the course includes steep grades. To ascertain the proper choice for a variety of conditions, we modelled the effects of 2 wheel sets on climbing performance. The light wheel set was assumed to have 500g less mass and 0.0063m^2 greater drag area than the aerodynamic wheel set. As in the previous section on climbing, we modelled road grades of 3, 6 and 12%. As shown in table VI, the aerodynamic wheels provided superior performance on the 3% road grade for all 3 modelled riders. For the 6% grade, the lighter, nonaerodynamic wheel was superior for the novice and trained cyclists, but the aerodynamic wheel was slightly superior for the elite cyclist. Finally, at 12%, the lighter wheels provided an advantage for all 3 riders. Thus, the optimal wheel interactively depends on the fitness or power output of the rider and on the grade of the climb.

5. Different Rules for Road Races

The model described and used may be applicable to time trials but prediction of road race performance with this model may be inaccurate. This is mainly because in road races many other factors will determine performance, including race tactics. In road races it is not always the individual who

Table V. Effects of body position on 40km time trial performance time in novice, trained and elite cyclists.[a] Performance time data are presented as min:sec

Positions modelled	Novice	Trained	Elite
Brake hoods	79:45	64:11	57:03
Handlebar drops	75:59	61:05	54:16
	–3:46	–3:06	–2:47
Standard aerodynamics	72:56	58:35	52:02
	–6:49	–5:36	–4:59
Optimised aerodynamics	70:24	56:29	50:09
	–9:21	–7:42	–6:54

a Changes in performance are expressed in time gain compared with standard position (rider's hands on the brake hoods).

Brake Hoods = rider's hands on the brake hoods (drag area 0.358m^2); **Handlebar Drops** = rider's hands on standard racing handlebar drops (drag area 0.307m^2); **Optimised aerodynamics** = a carefully optimised aerodynamic position (drag area 0.240m^2); **Standard aerodynamics** = a typical time trial position with elbows resting on supports (drag area 0.269m^2).

Table VI. The interactive effects of wheel weight, wheel drag area and road grade (3 to 12%) on time to ride 20km uphill in novice, trained and elite cyclists. Performance time data are presented as min:sec

	3% grade		6% grade		12% grade	
	aerodynamic	light	aerodynamic	light	aerodynamic	light
Novice	63:48	63:58	106:48	106:23	202:25	201:13
		+0:10		–0:25		–1:12
Trained	42:37	42:57	63:48	63:45	115:33	114:58
		+0:20		–0:03		–0:35
Elite	35:01	35:22	48:56	49:02	84:47	84:25
		+0:21		+0:06		–0:22

produces most power, or who has the best power to weight ratio or the best aerodynamics who wins. In road races skill, position of team mates and tactics are the predominant performance determining factors. We recently described an example of a World Class cyclist who participated in the Tour de France. In one of the level stages (6 hours) with little wind the average speed was 40 km/h. This cyclist with excellent drafting skills managed to reduce his average power output to just 98W.[16] It can be calculated that in optimal conditions with no wind and level roads, and with a good aerodynamic position, riding at that speed would require ≈275W.[18] It is, therefore, important to realise that cyclists will enter the final hour of road races, in which the race is often won or lost, having performed very different amounts of total work and consequently may be at very different levels of fatigue.

6. Conclusion

It may become apparent from this analysis that novice cyclists have significantly more scope for improvement than well-trained elite athletes. This effect is apparent both in internal as well as external factors. The improvements are larger for novice cyclists when they are expressed in absolute (seconds) or relative terms. However, the effects are not always additive. For example, a change in body position may result in a reduction in aerodynamic drag but may cause suboptimal joint angles and compromise power. On the other hand, the effects of training and carbohydrate feeding or training and changes in position may result in additive performance effects. Furthermore, the effects of altitude training may add to the effects of normal training.

It is also important to distinguish between factors that prevent a reduction in performance such as drinking in a hot environment, or heat acclimatisation (not discussed here) or factors that truly improve performance, such as training, improved aerodynamics, and caffeine.

In this review, we selected only a small portion of the potential factors that can influence exercise performance. However, we believe that these are the most important factors based on the current scientific literature. Support for the performance-enhancing effects of other supposed (legal) ergogenic aids was less robust, and therefore these factors have not been included in this analysis.

From the analysis in this review it becomes clear that training is probably the most important factor in improving cycling performance, but sometimes large improvements can be made by relatively small changes in body position. More expensive options of performance improvement include altitude training and modifications of equipment (light and aerodynamic bicycles and wheels). Depending on the availability of time and financial resources cyclists have to make decisions about how to achieve their performance improvements. The data presented here may provide a guideline to help make such decisions.

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Correspondence and offprints: Dr *Asker E. Jeukendrup*, Human Performance Laboratory, School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, England.
E-mail: A.E.Jeukendrup@BHAM.AC.UK

