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Comparing cycling world hour records, 1967–1996: modeling with empirical data

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Abstract

BASSETT, D. R. JR, C. R. KYLE, L. PASSFIELD, J. P. BROKER, and E. R. BURKE. Comparing cycling world hour records, 1967–1996: modeling with empirical data. *Med. Sci. Sports Exerc.,* Vol. 31, No. 11, pp. 1665–1676, 1999.

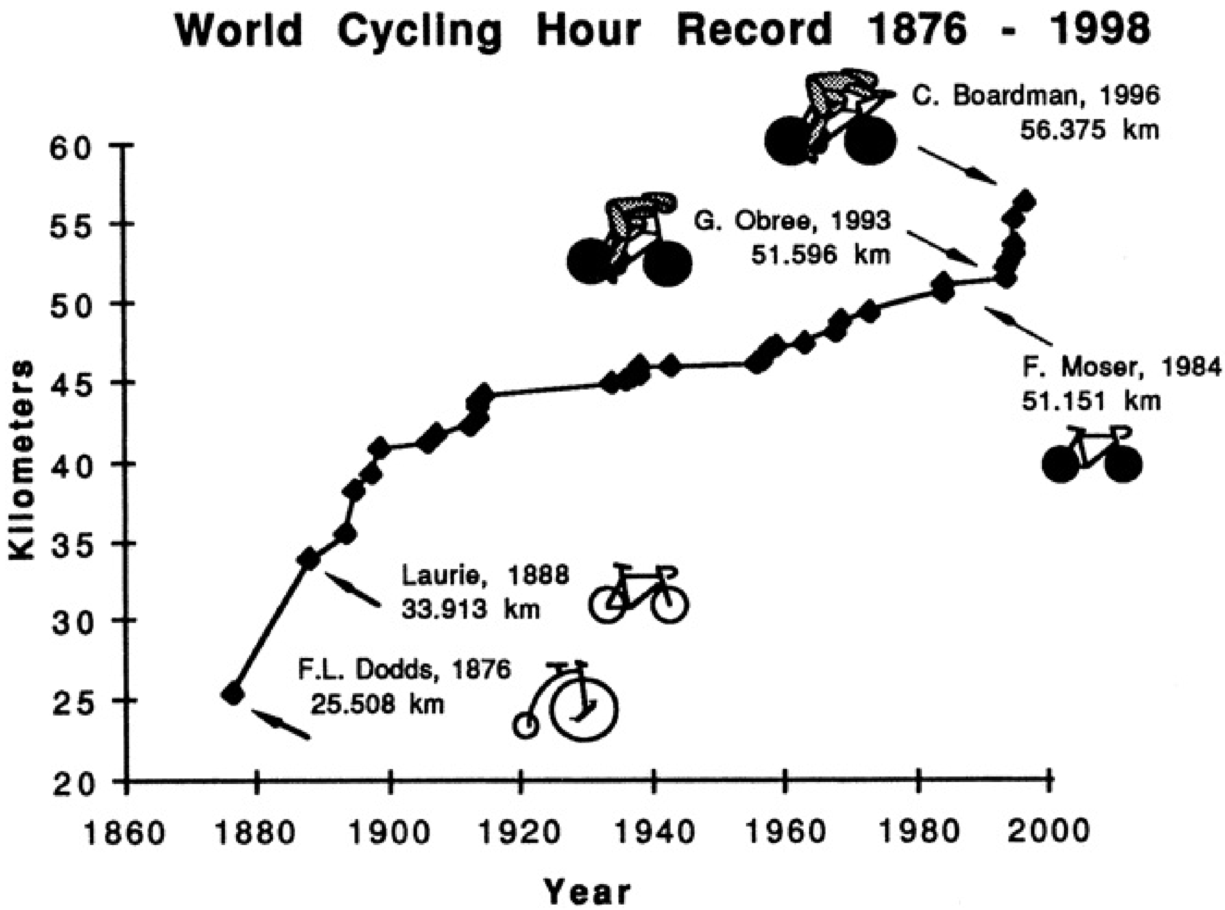
The world hour record in cycling has increased dramatically in recent years. The present study was designed to compare the performances of former/current record holders, after adjusting for differences in

aerodynamic equipment and altitude. Additionally, we sought to determine the ideal elevation for future hour record attempts.

The first step was constructing a mathematical model to predict power requirements of track cycling. The model was based on empirical data from wind-tunnel tests, the relationship of body size to frontal surface area, and field power measurements using a crank dynamometer (SRM). The model agreed reasonably well with actual measurements of power output on elite cyclists. Subsequently, the effects of altitude on maximal aerobic power were estimated from published research studies of elite athletes. This information was combined with the power requirement equation to predict what each cyclist's power output would have been at sea level. This allowed us to estimate the distance that each rider could have covered using state-of-the-art equipment at sea level. According to these calculations, when racing under equivalent conditions, Rominger would be first, Boardman second, Merckx third, and Indurain fourth. In addition, about 60% of the increase in hour record distances since Bracke's record (1967) have come from advances in technology and 40% from physiological improvements.

To break the current world hour record, field measurements and the model indicate that a cyclist would have to deliver over 440 W for 1 h at sea level, or correspondingly less at altitude. The optimal elevation for future hour record attempts is predicted to be about 2500 m for acclimatized riders and 2000 m for unacclimatized riders.

The hour record is one of the most prestigious events in cycling, having been attempted by many of the best racers in the world. Distances in this event have more than doubled since it was first established in 1876. Over the first century, improvements in the hour record gradually began to reach a plateau (Fig. 1). During the past 14 yr, however, dramatic improvements have been achieved. The more recent athletes have used radically different body positions and cycling equipment, greatly reducing the aerodynamic drag forces. In addition, some of the hour records were set in Mexico City (2300 m elevation), where the power requirement of track cycling is decreased because of a 20% reduction in air density. However, this advantage is partially offset by a decline in power output, due to decreased oxygen availability. Thus, it is unknown to what extent the improvements seen in recent years are due to increased power outputs of the cyclists, as compared to technological improvements.



The world cycling hour record from 1876 to 1998. The first record was set in 1876 by F. L. Dodds of England, riding a high-wheeled bicycle. From 1888 until 1984, conventional track bicycles were used. Starting in 1984, aerodynamic improvements such as disk wheels, aero handlebars, and aerodynamic bicycles were introduced.

Sport scientists have attempted to determine which cyclist had the best hour record performance (after correcting for equipment and elevation differences). Genzling (18) used a simple mathematical model to compare hour records up until 1984 and concluded that the true hour record holder was Ferdinand Bracke. However, Genzling's estimate of Bracke's power output (580 W) is very high, as is his estimate of Eddy Merckx's power in Mexico City (525 W). Peronnet et al. (30,31) conducted an analysis of hour record performances from 1942 to 1988 and concluded that Francesco Moser's 1988 Stuttgart record was the best up to that time. Later, Keen (20) used a rigorous scientific approach that combined empirical data collection and modeling, and found that Chris Boardman's 1993 performance exceeded those of two cyclists who came before him (Merckx and Obree).

To further extend this line of inquiry, we developed a mathematical model to predict the power requirements of track cycling that accounted for most of the major variables. These included velocity, altitude, cycling equipment, clothing, body position, height, weight, track circumference, and track surface. The effects of each variable on the drag forces experienced by the cyclist were determined through: 1) extensive wind-tunnel testing to determine the effects of specific variables on the drag coefficients, 2) empirically determined relationships between body dimensions and frontal surface area and, 3) measurements of power output during actual track cycling, using a crank dynamometer. The model was compared with direct field measurements performed on elite trained cyclists, to ensure the model predicted the actual power requirement of track cycling reasonably well.

To determine the effects of altitude on power output, we estimated the reduction in power output at higher elevations. The decline in maximal aerobic power ($\dot{V}O_{2max}$) with increasing elevation was estimated from the results of scientific studies on elite runners or cyclists. Although this approach has been used before (Peronnet et al. (30,31), Capelli and di Prampero (8)), previous studies used the altitude-related decline in $\dot{V}O_{2max}$ for average-fit males.

The first aim of the present study was to determine the power requirements of track cycling using direct field measurements, so as to permit comparisons of world hour record performances. These tests were conducted at five different locations from near sea level to high elevation on four continents (2,3,5,20). We combined this information with our estimates of the altitude-induced decline in power output, to compute what each cyclist's power output would have been if they had ridden at sea level. This allowed us to estimate the distance that each rider could have covered using similar equipment at sea level. A secondary aim of the study was to predict the ideal elevation for future hour record attempts.

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METHODS

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Theoretical model for predicting power required for track cycling.

The power required to cycle on a bicycle racing track depends upon many variables; some of the more important ones are: speed; cyclist's riding position and body size; type of bicycle; wheels, tires, and components; altitude, track design, and condition; and environmental conditions such as wind velocity, temperature, and humidity, etc. Heretofore, estimates of the mechanical power required to cycle were based upon indirect measurements such as oxygen uptake, laboratory ergometer studies, wind tunnel measurements, coast down tests, towing tests, or upon theoretical models based upon these indirect measurements (7,9,21,23,24,28,34,35). However, since the advent of the bicycle crank dynamometer, it is no longer necessary to use theoretical or indirect estimates of the power required; it can be measured directly with accuracy.

Theoretical models, however, can still be very useful when researchers, coaches, or athletes want to estimate the required power under a variety of conditions without direct measurement. Models can also be useful in comparing past cycling performances for which power data are not available. It is the purpose of this section to develop a model for cycling power versus speed on a track, using field power measurements conducted with an SRM crank dynamometer system (described later). The tests were performed by Jeff Broker of USOC Sports Sciences, on U.S.A. Team cyclists (2–5), and by Louis Passfield of the University Medical School in Aberdeen and Peter Keen (20) of the British Cycling Federation on British Team cyclists. Hence, this study represents secondary data analysis of existing data bases, which were collected by coaches and technical staff for the purposes of preparing their athletes for national and international competition. Table 1 summarizes the resulting SRM power data used for developing the model. The column labeled Power gives the average measured power required in W to go 52.27 kph. This was the speed of Chris Boardman's world hour record set in Bordeaux, France, July 23, 1993, and it is used as a reference by Passfield and Peter Keen (20). The speed is also typical of National Caliber individual pursuit racers and is the equivalent of 4 min and 35 s in a 4000-m pursuit. In this paper, speeds are given in kilometers per hour (kph), because this is the most familiar form for velocity in bicycle racing.

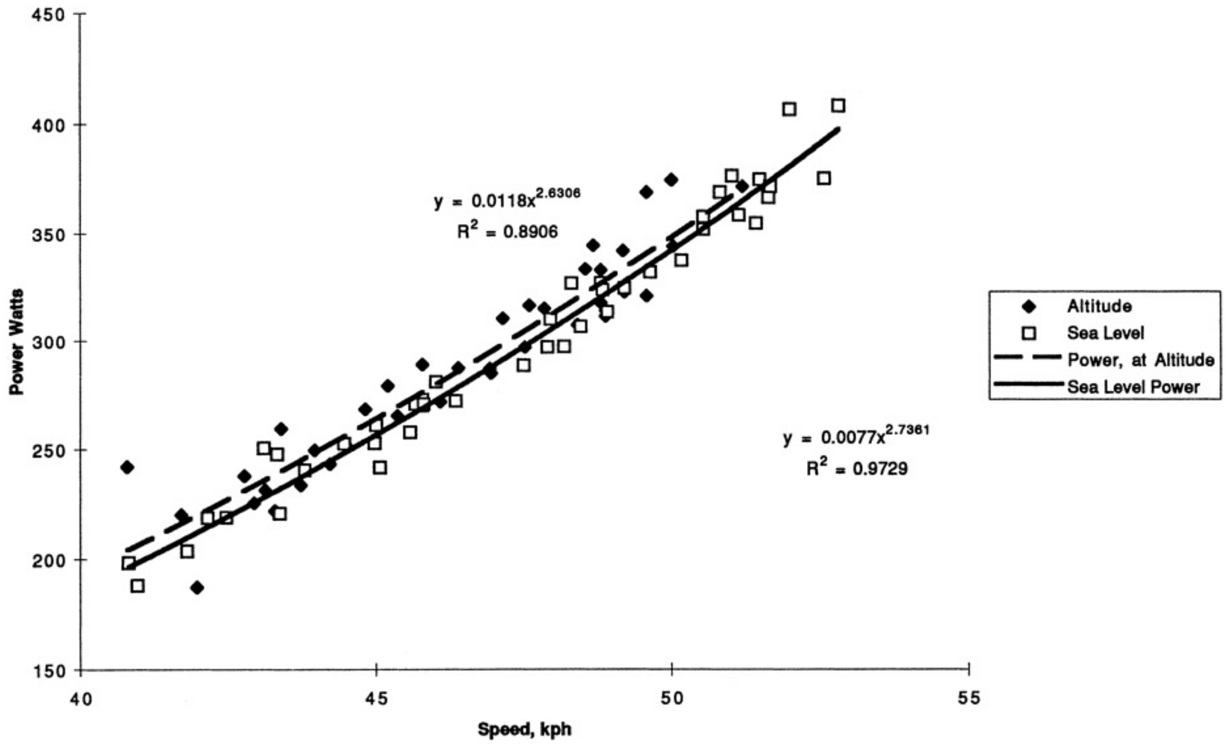
TABLE 1. Power versus speed for track cyclists; all results at 52.27 kph.

Test No.	Cyclist	Bike	Height (m)	Mass (kg)	Location	Power Equation	Constants K	Constants K1	Measured Power (W)	Eq. 8 (W)	Error %	Reference
1	Subj. 1	Lotus[a]	1.735	70	Manchester	$P = .01720V^{2.5284}$	1.0	0.924	380	386	+1.6	[33]
2	Subj. 1	Lotus			Manchester	$P = .00770V^{2.7361}$	1.0	0.924	387	386	−0.3	[33]
3	Subj. 1	Lotus			Colombia	$P = .0118V^{2.6306}$	1.25	0.723	391	392	−25	[33]
4	Subj. 1	Std track			Manchester	$P = .01580V^{2.5585}$	1.0	0.994	393	411	+4.6	[33]
5	Subj. 2	Std track	1.88	83	Manchester	$P = .01770V^{2.5878}$	1.0	0.994	494	457	−7.5	[33]
6	Subj. 3	Std track	1.88	79	Manchester	$P = .01380V^{2.6237}$	1.0	0.994	445	448	+0.7	[33]
7	Subj. 4	Std track	1.82	76	Manchester	$P = .02040V^{2.5000}$	1.0	0.994	403	434	+7.7	[33]
8	Subj. 5	Std track	1.80	69	Manchester	$P = .01990V^{2.5266}$	1.0	0.994	437	414	−5.3	[33]
9	Boardman	Corima	1.75	68	Bordeaux	$P = .01015V^{2.6802}$	1.0	0.993	409	408	−0.2	[20]
10	Boardman	Obree position			Bordeaux	$P = .01287V^{2.6106}$	1.0	0.953	394	394	0.0	[20]
11	Boardman	Std track Merckx			Bordeaux	$P = .00525V^{2.8837}$	1.0	1.180	473	473	0.0	[20]
12	Subj. 6	Std track 1993	1.80	74	Colorado Springs	$P = .0117V^{2.6339}$	1.0	0.836	393	369	−6.1	[3]
13	Subj. 6	1996 SB2*			Colorado Springs	$P = .0136V^{2.5780}$	1.0	0.777	366	348	−4.9	[3]
14	Avg. 3	Std track 1993	1.83	79	Adelaide	$P = .0049V^{2.9190}$	1.0	1.0	508	444	−13	[2]

[a] The Lotus and SB2 are composite aero bikes with disk or tri-spoke rear wheels and tri-spoke or bladed-spoked front wheels. The standard track bikes had rear disks and tri-spoke or bladed spoke front wheels. The Merckx bike was a traditional track bike with conventional wheels with steel spokes.

Power versus speed for track cyclists; all results at 52.27 kph.

The power required by various cyclists to go 52.27 kph, as listed in Table 1, ranges from about 360 W to over 500 W. With such data scatter, one cannot expect a model to predict required power accurately under all circumstances because the experimental results depend so much upon individual rider position, ambient environmental conditions, and the condition of the track. In one example (tests 1, 2, and 3, Table 1), Louis Passfield measured a cyclist using identical equipment in Manchester, England, which is near sea level, and on a practice track in Duitama, Colombia, at an elevation of about 2500 m. The power required at altitude was actually higher than the power at sea level (Fig. 2), although theoretically the wind resistance should be about 23% less at 2500 m. Passfield attributes the surprising result to a very rough track with tight curves. Wind conditions could also have increased the required power. Another example would be the tests at Adelaide, Australia (test 14), where required power is higher than expected. Despite the inherent certainty of errors, it will be well worthwhile to examine mathematical models of cycling performance.



Cycling crank power input measured by a crank dynamometer at sea level on the indoor track at Manchester, England, and at about 2500 m on the outdoor track at Duitama, Colombia. The rider used the same equipment at both locations (Table 1). Contrary to theory, the measured power at altitude was higher than the power at sea level. Measurements by Louis Passfield.

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Direct measurement of power.

For the data listed in Table 1, the measurement protocol used by all of the test directors was similar. The SRM crank dynamometer (Schoberer Rad MeBtechnik, Welldorf, Germany) consists of an instrumented chainring that transmits strain-gauge readings by telemetry to a handlebar microprocessor or to a central computer, along with crank RPM and bicycle speed. From this, average power can be computed and stored.

The SRM system was calibrated before each set of tests. SRM power for 1-s intervals was averaged for each lap. Passfield and Keen had the cyclists start at about 40 kph and increase their speed gradually (about 0.1 s faster per lap) until they reached approximately 53 kph. The cyclists increased speed continuously, without resting between laps. Broker had the cyclists ride steady lap speeds in 5-kph increments, starting at about 30 kph, and increasing until about 50–55 kph. The cyclists rode at each speed for at least two laps and rested for two laps between intervals. The speeds were ridden in a sequence which varied according to each rider's preference.

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Exponential equation.

The power/speed data points for each lap were plotted, and an exponential equation of the form $P = Cv^n$ was fit to the data, where P is the crank power in W, C is a proportionality constant, V is the speed in kilometers per hour (kph), and n is an exponent. The regressions for all of the data sets had a mean r^2 value of 0.9754. The exponential equations fit to each data set are given in Table 1. Typical curves and data points are shown in Figure 2.

Tests 4 through 8 in Table 1 were conducted by Louis Passfield at the indoor track in Manchester, England, with similar bicycles but with five different cyclists. Using all data points from the five subjects gives an exponential power equation of:

MATH 1

$$P = 0.0172V^{2.561} \qquad (1)$$

The mean height of the five subjects is 1.82 m and the mean mass 75.4 kg.

Although exponential equations are convenient for predicting power accurately over the range of the tests, there is no real physical significance to the coefficient or the exponent. If the equation were modified to account for changes in wind resistance, rider weight and height, track conditions, or other physical variables, it would produce a purely empirical expression, which is difficult to interpret physically. The authors did develop an exponential model, which matched experiment fairly well. However, the choice of coefficients was somewhat arbitrary, so it will not be presented here.

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Power series equation.

The following power series equation does have a firm physical basis:

MATH 2

$$P = A_1V + A_2V^2 + A_3V^3 \qquad (2)$$

A_1 is a constant expressing the static rolling resistance of bicycle wheels and tires (a bicycle wheel has a frictional resistance to motion even when standing still). A_2 is a constant related to the dynamic rolling resistance (rotating bicycle tires, wheels, and bearings increase their frictional resistance as the speed increases). A_3 is a constant that is a function of the air density, the frontal area of the rider and bicycle, and the aerodynamic drag coefficient (related to the shape of an object and the efficiency with which it moves through the air) (22,24).

The constant A_1 may be derived from experimental data (24). Racing bicycle tire tests show that rolling resistance increases with the weight on the tire, the steering angle, the roughness of the surface, and other factors (24). There are several things that tend to cause rolling resistance on a bicycle racing track to be higher than measured on a straight level test surface. 1) On a track, in the curves, the centrifugal force raises the weight on the tire by over 1.5 times at racing speeds. 2) The steering angle of a bicycle at racing speed, oscillates through about ± 3° with every pedal stroke, causing increased rolling friction due to tire scrubbing. Scrubbing occurs, when the tire contact patch acquires a slip angle with the pavement as the bicycle turns. 3) Bicycle tracks are always cambered (banked) even on the straights. The fact that the bicycle is almost never perpendicular to the track means that a steering correction is required to hold the bicycle on a line, which causes added tire friction. 4) Also, most racing tracks are not entirely smooth. Even though static rolling resistance can be as low as 0.22% of the down force applied to the tire (24), a more reasonable estimate for conditions on a bicycle track would be an average of 0.35% of the applied force on the tire. This would give a value for A_1 of (0.00953 M_t) W h·(kg km)$^{-1}$, where M_t is the total mass of the bicycle and rider in kilograms (we will assume the bicycle weighs 10.0 kg, because no direct measurements of the bicycle weights are available).

A_2 is proportional to the increase in rolling resistance due to bearing friction, dynamic tire deformation, and the windage of a spinning wheel. It has been measured for a 17-inch Moulton bicycle wheel with wheel covers by Richard Moore of General Motors (27). Because no other reliable data are available, the constant derived from Moore's report shall be used, A_2 = 0.00775 $W \cdot km^{-2} \cdot h^{-2}$ (2).

Using and the values for A_1 and A_2, one can now solve for A_3 directly, based upon the average experimental data. gives a power of 432 W at 52.27 kph. This gives a value for A_3 of 0.002582. Substituting the values for the constants in gives:

MATH 3

$$P = 0.00953M_tV + .00775V^2 + .002582V^3 \qquad (3)$$

To be able to correct the equation for rider size, altitude, bicycle type, riding position, temperature, and other variables requires further development. Neither A_1 nor A_2, which are related to tire rolling resistance, require modification; however, A_3, which is related to aerodynamic drag, should be adjusted for changes in altitude, bicycle and component types, rider position, rider size, atmospheric conditions, etc.

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Factors influencing aerodynamic drag.

Because A_3 is a function of the aerodynamic drag of the bicycle and rider it may be expressed as (19,22,24):

MATH 4

$$A_3 = 1/2\rho C_d A_f \qquad (4)$$

where ρ is the air density, C_d is the aerodynamic drag coefficient and A_f is the frontal area of the bicycle and rider.

In the range of speeds in endurance track racing (50–60 kph), the drag coefficient of cyclists C_d is typically constant as long as the rider position, equipment, and environmental conditions are constant. This was shown by full scale tests in the General Motors Automotive wind tunnel, Warren, MI (4). For a fixed riding position, when the air drag was plotted versus velocity squared in the range from 40 to 56 kph, the result was linear with the average $r^2 = 0.998$. We will discuss the influence of rider position and cycling equipment on the drag coefficient and frontal area in more detail later. First, we will consider the effects of air density.

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Air density.

Air density varies with altitude according to atmospheric temperature and pressure. The air density ratio may be estimated from the following polytropic gas equation, which is used for calculating low level density variation in the U.S. Standard Atmosphere (29):

MATH 5

$$\rho_2/\rho_1 = [1 - g(n-1)(z_2 - z_1)/(nRT_1)]^{(1/(n-1))} \qquad (5)$$

where ρ is the air density in $kg \cdot m^{-3}$, g is the acceleration of gravity 9.807 $m \cdot s^{-2}$ at sea level, n is a polytropic gas coefficient, $N = 1.235$, z is the elevation above sea level in meters, R is the gas constant for air R = 287.1 $Nm(kg \cdot K)^{-1}$, and T is the absolute temperature in Kelvin T = 288°K (15°C). For example: z = 1829 m for Colorado Springs and the density ratio would be $\rho_2/\rho_1 = 0.836$, compared with sea level. This means that the density, and therefore the air resistance, should be about 16.4% less in Colorado Springs than at sea level for the same rider and bicycle combination.

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Frontal area.

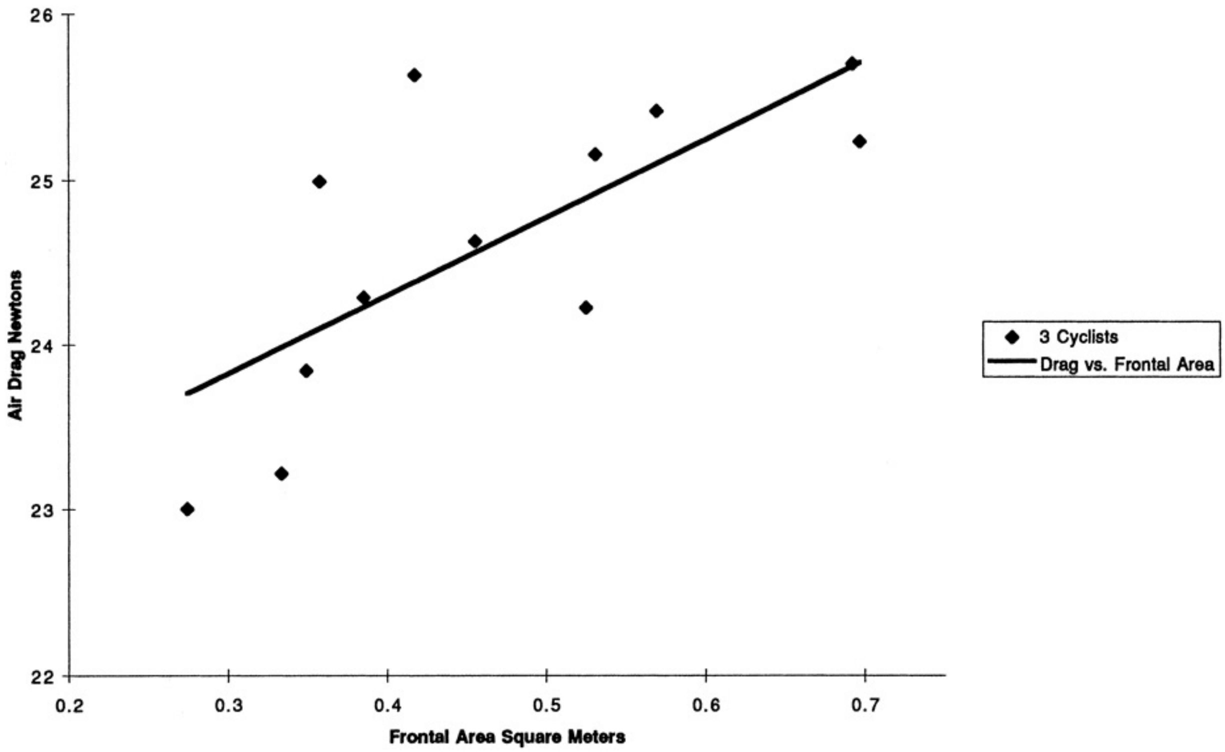
Table 2 shows the frontal area and air drag of three cyclists measured in the Texas A&M wind tunnel in 1990 (23). The cyclists used road time trial bikes with triathlon aero bars, a rear disk wheel, and a bladed-spoked front wheel. They wore one-piece Lycra cycle clothing with Giro aero helmets. The frontal area was measured by taking telephoto photographs of the cyclists outdoors at a distance of 50 m, with a reference area held at the midpoint of the crank. To find the frontal area, the photographs were cut out and the paper figures weighed on a laboratory balance and compared with the weight of the reference area. Using the data in Table 2, Figure 3 shows a plot of the air drag versus the frontal area of the bicycle plus rider (23). The linear regression shows that air drag increases linearly with frontal area. The correlation is only fair with $r^2 = 0.524$; however, the approach should still be useful. Broker of the USOC Sports Sciences also measured the frontal area of cyclists (not including the bicycle), along with the wind tunnel air drag (4) (see Table 3). Broker's data also yields a linear relation for air drag versus frontal area, with $r^2 = 0.572$. We can assume then, with reasonable accuracy, that air drag is proportional to frontal area.

TABLE 2. Frontal area and air drag of three cyclists (24).

Subject	Yaw Angle	Height (m)	Mass (kg)	Body Surface Area (m^2)	Body Frontal Area (m^2)	Bike Frontal Area (m^2)	Total Frontal Area (m^2)	Drag (N at 48 kph)
RR	0°	1.803	69.0	1.88	0.292	0.066	0.358	24.99
	10°				0.315	0.103	0.418	25.64
	20°				0.333	0.199	0.531	25.16
	30°				0.360	0.360	0.697	25.24
KS	0°	1.753	59.9	1.73	0.268	0.066	0.334	23.22
	10°				0.289	0.096	0.385	24.29
	20°				0.328	0.197	0.525	24.22
	30°				0.355	0.338	0.693	25.71
MR	0°	1.626	47.6	1.05	0.206	0.066	0.272	23.00
	10°				0.264	0.085	0.349	23.84
	20°				0.266	0.191	0.455	24.63
	30°				0.289	0.280	0.569	25.42

All cyclists had round tube triathlon bicycles with aero bars, rear disk wheels, and front aero blade spoked wheels.

Frontal area and air drag of three cyclists (24).



The air resistance of three cyclists versus the total frontal area of the cyclist plus the bicycle. Measurements by C. R. Kyle, at the Texas A&M wind tunnel, 1990 (23).

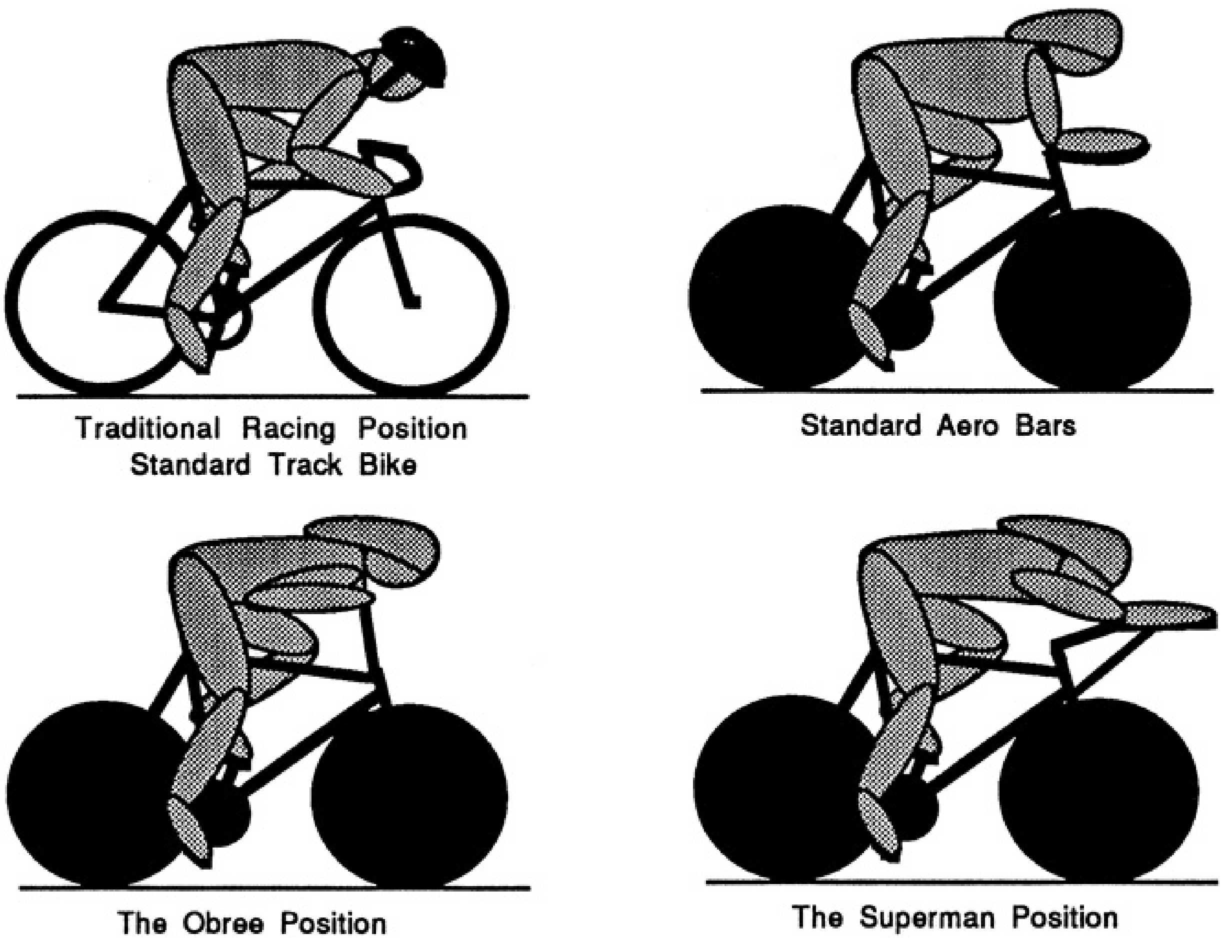
TABLE 3. Frontal area and air drag of five cyclists (4).

Subject	Height (m)	Mass (kg)	Body Frontal Area (m^2)	Drag (N at 48 kph)
6	1.80	74.0	0.240	21.01
7	1.80	77.0	0.229	21.35
8	1.80	74.0	0.260	23.52
			0.235	20.42
9	1.86	81.0	0.234	21.35
			0.214	20.24
10	1.93	87.0	0.260	23.52
			0.230	22.79

Cyclists had composite track bikes with airfoil shaped tubing, aero bars, rear disk wheel, and aero blade spoked wheels.

Frontal area and air drag of five cyclists (4).

Air drag will change with body size and riding position, as shown by Swain et al. (34,35). Both rider size and riding position will significantly affect the frontal area but will also influence the drag coefficient. As a cyclist changes position, two things happen; the frontal area changes, and at the same time the drag coefficient also changes because the new pattern of airflow is not geometrically similar to the previous condition. This means it is not possible to separate the effects of drag coefficient and frontal area where rider position is concerned. Any changes therefore should be lumped into one factor (often called the drag area C_dA_f). However, by selecting one cycling position as a standard, we can handle the effects of body size and riding position separately. For simplicity, as a standard we will use the triathlon racing position (elbows on triathlon aero bars, arms inside the projected frontal body area, torso flat, head tucked low between shoulders). See Figure 4 for the common cycle racing positions.



Bicycle racing positions. From the 1890s until 1986, cyclists used the same traditional crouched racing position. Starting in 1986, aero bars (invented by Peter Pensayres and used in the Race Across America in 1986) allowed cyclists to rest on their elbows while maintaining a low aerodynamic riding posture. Graham Obree of Scotland pioneered two unique riding positions, which he used to set hour records in 1993 and 1994 (the Obree position and the Superman position).

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The effect of body size on frontal area.

To be able to estimate a riders' frontal area easily, by utilizing their height and weight, we can adapt the expression of Dubois and Dubois (16) for human body surface area:

MATH 6

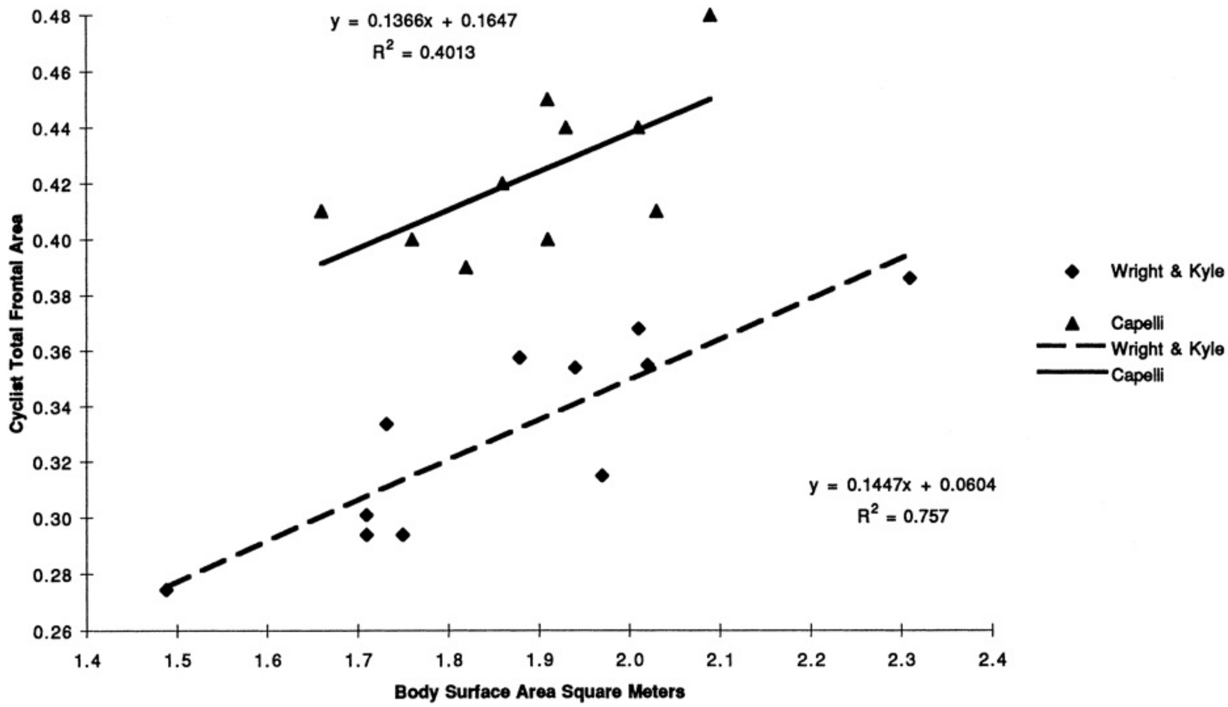
$$A_s = 0.2025 H^{0.725} M^{0.425} \qquad (6)$$

The surface area A_s is in m^2, H is the height in m, and M is the mass in kg. Using data from Wright et al. (41) and Kyle (23) (Tables 2 and 4), Figure 5 shows a linear relation between the surface area of cyclists to the total frontal area of the cyclists plus bicycle, for a yaw angle of 0°. The regression equation in Figure 5 gives an $r^2 = 0.757$. In other words, the total frontal area of cyclists plus bicycle, in the standard time trial aero racing position, is proportional to the surface area of the cyclists with reasonable accuracy. Applying the regression equation to gives an expression for the total frontal area in terms of the cyclist height and mass:

TABLE 4. Total frontal area and surface area of cyclists (41).

Subject	Height (m)	Mass (kg)	Total Frontal Area (m^2)	Surface Area (m^2)
11	1.82	80.0	0.368	2.01
12	1.85	78.1	0.355	2.02
13	1.76	57.9	0.294	1.71
14	1.73	63.1	0.294	1.75
15	1.78	79.4	0.315	1.97
16	2.00	94.0	0.386	2.31
17	1.78	75.8	0.354	1.94
18	1.70	61.2	0.301	1.71

Total frontal area and surface area of cyclists (41).



The total cyclist projected frontal area (body plus bicycle) plotted against the cyclist's body surface area. The cyclists in the lower curve (Wright et al. (41) and Kyle (23)) used standard aero bars, whereas those in the upper curve (Capelli et al. (9)) used the older traditional racing position.

MATH 7

$$A_f = 0.0293H^{0.725} M^{0.425} + 0.0604 \qquad (7)$$

Also shown in Figure 5 are the data of Capelli et al. (9) for elite racing cyclists using standard racing bicycles. Capelli et al. plotted frontal area versus body surface area and obtained a reliability coefficient of $r^2 = 0.401$. The riders in Capelli's study apparently did not use aero bars, and thus the frontal areas were significantly higher than in the present study. However, it can be seen from Figure 5, that the slope of the linear regression curves is very similar. Both Capelli et al. and Swain et al. note that the ratio of body surface area to frontal area favors larger subjects who have a lower frontal area related to their body size than do smaller subjects, and unless this is taken into account, any performance model will tend to overestimate the power required of larger subjects to overcome wind resistance. accounts for this difference.

In the present study, the average cyclist size is height = 1.82 m and mass = 75.4 kg, the average frontal area is $A_f = 0.344$ m^2, and the density correction for Manchester is 0.994. Using equations 4 and 7, can now be modified for changes in wind resistance due to rider size, altitude, equipment type, position, etc., as follows:

MATH 8

$$P = K(0.00953\ M_t V + .00775V^2 + K_1(A_f).007551V^3) \qquad (8)$$

where K is a factor which allows adjustment for track roughness or other external conditions and K_1 is an aerodynamic factor which incorporates a correction for altitude (the density ratio), and corrections for rider position, bicycle type, components, clothing, helmets, etc. No effect of winds will be included in either of the factors K or K_1 because on an oval racing track the effect of wind is unpredictable. K_1 can be expressed as:

MATH 9

$$K_1 = K_d K_{po} K_b K_c K_h \qquad (9)$$

where K_d is the density ratio compared with sea level (equation 5), K_{po} is the effect of position, K_b is the effect of the bicycle and components, K_c is the effect of clothing, and K_h is the effect of the helmet. Table 5 lists a few of the more important factors affecting aerodynamic drag. The correction factors listed in Table 5 were obtained by tests of bicycles, cyclists, wheels, and helmets in the General Motors wind tunnel (Warren, MI, 1994–1996, [ref. 4 and internal reports]). Obviously, by improving position, bicycles, wheels, components, clothing, helmets, etc., a time trial bicycle can be much faster. The factors listed in Table 5 are valid in the range of racing speeds from 50 to 60 kph.

TABLE 5. Correction factors to cycling aerodynamic drag (4).

Density ratio	K_d
Sea level	1.0
Colorado Springs, 1829 m	0.836
Mexico City, 2340 m	0.794
Bogata/Duitama, Colombia, 2500 m	0.781
Rider position	K_{po}
Standard position with aero bars, elbows in (inside body contour)	1.0
Standard position with aero bars, elbows wide (outside body contour)	1.07–1.11
Historic racing position with drop bars, varying torso and head angle	1.08–1.18
Obree Position	0.96
Superman Position	0.95
Bicycle and components	K_b
Round tube standard track bike, aero bars, disk or composite wheels	1.0
Round tube standard track bike, drop bars, wire-spoke wheels	1.07
Composite double triangular frame, oval frame members (Corima)	1.0
Aluminum aero tube bike (Hooker, USA-SB1)	0.93
Lotus composite aero bike (1992 Olympic, Boardman)	0.93
Advanced composite aero bike, USA SB2, 1996 Merckx (Boardman)	0.925
Bicycle clothing	K_c
Short Sleeves, 3/4 legs, nylon Spandex skin suit	1.0
Same design, optimum weave material	0.98
Cotton jersey, separate shorts	1.02
Wool jersey, full tights, full sleeves	1.09
Bicycle helmets	K_h
Aero time-trial helmet (USA, England, German, French, Italian)	1.0
Modern slotted protective helmet	1.025
Historic leather strap helmet	1.04

The above correction factors to the aerodynamic drag assume an average air drag for a rider and bicycle of approximately 2.5 kg (24.5 N) at 48 kph. By multiplying the above factors together, an overall correction K_1 may be obtained.

Correction factors to cycling aerodynamic drag (4).

Table 1 shows the result of using this model in predicting power measurements from five locations: Manchester England; Duitama, Colombia; Bordeaux, France; Colorado Springs, CO; and Adelaide, Australia (see Table 6 for track specifications). The Manchester track was used as a reference K = 1.0, and the correction factors in Table 5 and altitude corrections were applied. The absolute power prediction error is shown in Table 1.

TABLE 6. Characteristics of cycling tracks.

Location	Length (m)	Cover	Surface	Elevation (m)
Adelaide, Australia	250	Indoors	Wood	4
Atlanta, GA	250	Outdoors	Wood/resin	313
Bordeaux, France	250	Indoors	Wood	73
Colorado Springs, CO	333	Outdoors	Concrete	1829
Duitama, Colombia	250	Outdoors	Concrete	2500
Hamar, Norway	250	Indoors	Wood	124
Manchester, England	250	Indoors	Wood	60
Mexico City, Olympic Velodrome[a]	333	Outdoors	Wood	2338
Mexico City, Olympic Sports Center[b]	333	Outdoors	Varnished concrete	2338
Rome, Italy	333	Outdoors	Concrete	48
Stuttgart, Germany	285	Indoors	Wood	121

Elevations were determined from the Defense Mapping Agency Operational Navigation Charts, which include the elevation for all airports of the world (39). The nearest airport to the cities above were used as benchmarks.
[a] Site of Ritter's (1968) and Merckx's (1972) records.
[b] Site of Moser's 1984 records.

Characteristics of cycling tracks.

Except for Duitama, Colombia (test 3), and Adelaide, Australia (test 14), the absolute error of prediction was no higher than 7.7% and averaged 3.9% (SD 2.9), which is reasonable considering the data variability. Neither Duitama nor Adelaide were included in the average. In the case of the outdoor track at Duitama, Colombia, the required power was an extraordinary 25% higher than estimated by the model, which, as mentioned, could have been caused by a rough track with tight turns or variable windy conditions (in Fig. 2, the data scatter outdoors at Duitama was greater than indoors at Manchester). Another possibility would be an instrument calibration error, but Passfield took pains to calibrate the SRM before each series of tests. In the case of the sea-level indoor track at Adelaide, the required power was 13% higher than calculated by the model. There seems to be no reasonable explanation for this discrepancy, except perhaps the team was inexperienced and may have used inefficient riding positions or riding techniques.

In the field measurements by Peter Keen of Chris Boardman in Bordeaux (20), Keen had Boardman ride in the standard aero position as well as in the Graham Obree position (arms folded against the body with the shoulders resting on the hands; see Fig. 4). The required power decreased from 409 W to 393 W at 52.27 kph. This represents about a 4% drop in wind resistance (K_1 = 0.96). He also had Boardman ride a standard track bike with drop bars and wire-spoked wheels similar to the one Eddy Merckx rode in his 1972 hour record set in Mexico City (49.431 km). In this test, the required power was 473 W, which is equivalent to an increase in wind resistance of 18% (K_1 = 1.18).

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Power required for the hour record.

Chris Boardman set the current world hour record of 56.375 km at Manchester in 1996 using a new Lotus/Merckx aero bike and the Superman position (arms extended forward in diving posture with the head tucked between the arms—the elbows and hands are far forward of the steering axis; see Fig. 4). Wind tunnel data show that the Superman position, on an aero bike, lowers the overall wind resistance about 5% compared with the standard aero position (K_{po} = 0.95) (4). Also an efficient composite aero bike would lower the wind resistance about 7% compared with a standard track bike (K_b = 0.93) (4). The density ratio for Manchester is K_d = 0.994. This gives a combined $K_1 = 0.994 \times 0.95 \times 0.93 = 0.878$. According to the model, the required power would be 452 W at 56.375 kph. In a personal communication to Craig Turner, Peter Keen estimated that Boardman produced about 442 W during his latest hour record (37); so in this case, the model predicts high by about 2%.

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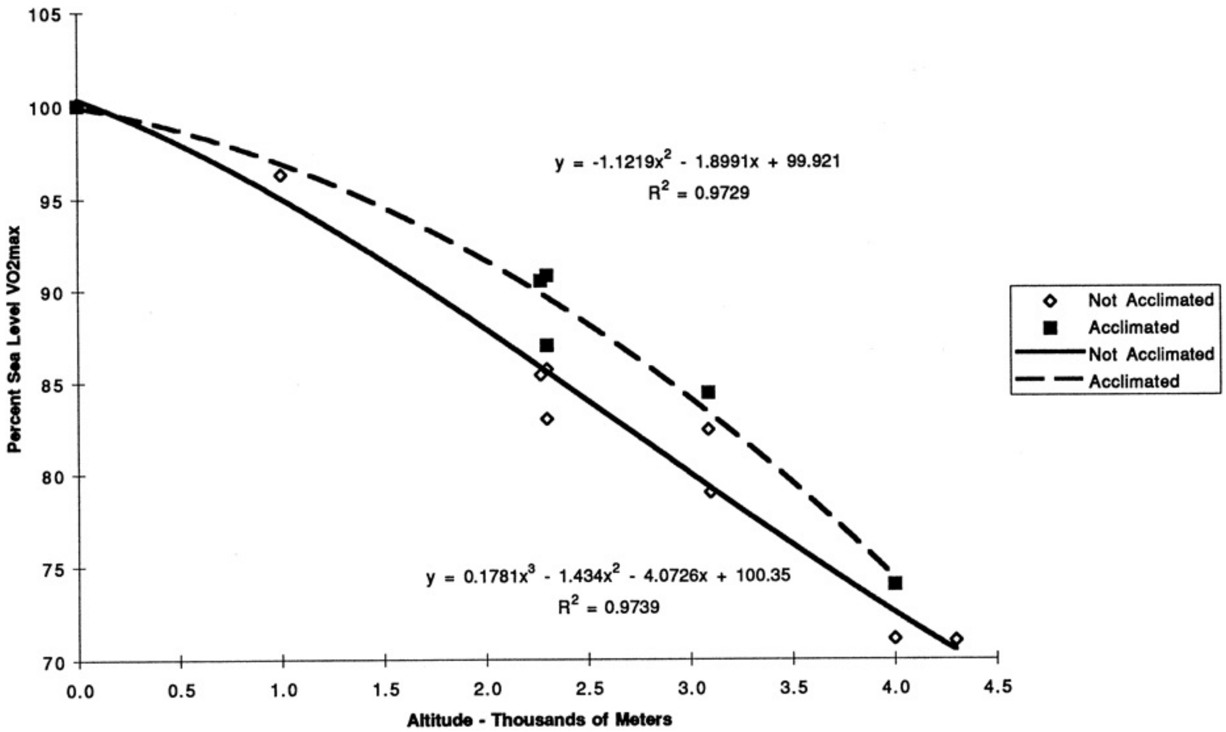
Effects of altitude on power output.

The percent decline in $\dot{V}O_{2max}$ at various elevations is shown in Figure 6. Measurements were made at sea level and within 2–7 d after arrival at altitude. The average sea level $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) values were 74.4 (Daniels and Oldridge (13)), 72.0 (Dill and Adams (15)), 69.8 (Chapman et al. (10)), 63 (Buskirk et al. (6)), 65 (Pugh (32)), and 66.2 (Faulkner et al. (17)). Chapman et al. (10) used an inspired O_2 concentration of 18.7% at sea level (simulating an elevation of 1000 m). The other studies were conducted at elevations ranging from 2270 to 4300 m. An equation describing the relationship between altitude and maximal aerobic capacity is:



The decrease in maximal oxygen uptake versus altitude for elite athletes. The upper curve is for athletes who have trained for several weeks at altitude and who are acclimated. The lower curve is for athletes who have spent only 1–7 d at altitude before the measurements were taken. Adapted from E. T. Howley. Effects of altitude on physical performance. In:Encyclopedia of Physical Education, Fitness and Sports: Training, Environment, Nutrition, and Fitness, G. A. Stull and T. K. Cureton (Eds.). Reston VA: AAHPERD, 1980, p. 180. Copyright 1980 by AAHPERD; reprinted by permission.

MATH 10

$$Y = (0.1781)X^3 - (1.434)X^2 - (4.073)X + 100.352 \quad (r^2 = .9739) \quad (10)$$

where Y is the percent of $\dot{V}O_{2max}$ measured at sea level and X is the altitude in kilometers. This equation predicts a $\dot{V}O_{2max}$ in Mexico City (2338 m) that is 85.3% of the sea level value, or a 14.7% decline.

Only studies on highly trained athletes were examined, because the altitude-related decline in $\dot{V}O_{2max}$ in this group may differ from that of normal individuals. In trained individuals, their greater maximal cardiac output values tend to reduce red blood cell transit time in the pulmonary capillary. This makes it difficult to saturate the blood with oxygen, particularly at altitude where the partial pressure of oxygen is reduced (14). In other words, athletes function on a steeper portion of the oxyhemoglobin dissociation curve, and they are more likely to desaturate when the inspired PO_2 is reduced. Lawler et al. (25) and Martin and O'Kroy (26) demonstrated that when exposed to hypoxic conditions (13% O_2), the decline in $\dot{V}O_{2max}$ is almost twice as great for trained athletes, compared with untrained men. These investigators find a strong, inverse linear relationship between maximal aerobic power and the change in $\dot{V}O_{2max}$ upon exposure to reduced oxygen ($r = -0.91$ to -0.94). Hence, there is good evidence that elite cyclists undergo a greater decline in $\dot{V}O_{2max}$ upon exposure to altitude than ordinary subjects.

The relationship given by is for the effects of acute exposure, wherein $\dot{V}O_{2max}$ was measured within several days of arriving at altitude. However, the acclimatization response to high altitude must also be considered. Merckx set his hour record a few days after arriving in Mexico City, whereas Moser trained for a month in Bogota (3000 m elevation) before his records (11) and Ritter trained for three weeks in Mexico City before his ride (O. Ritter, personal communication).

Several authors have studied the time course of the physiological response to training at high altitude. Dill and Adams (15) studied high school champion runners at 3100 m and found that $\dot{V}O_{2max}$ was decreased by 17.6% after 2 d and 15.6% after 16 d. Buskirk (6) studied Penn State trackmen at 4000 m and found that $\dot{V}O_{2max}$ was decreased from sea-level values by 29% on the 2nd day, 29% on the 21st day, and 26% on the 48th day. Pugh (32) studied six international middle-distance runners in Mexico City and found a reduction of 14.6% on the 2nd day and 9.5% on the 27th day. Daniels and Oldridge (13) found a 14.3% drop in world-class runners within 1–2 d of arrival in Mexico City. By the 5th week of alternating high and low-altitude exposure, they still had a 9.2% drop in $\dot{V}O_{2max}$. Faulkner et al. (17) studied elite runners in Mexico City and found a 17% decline initially and a 13% drop after 34 d. Taken together, these studies suggest that high-altitude training enables athletes to regain some of the decline in $\dot{V}O_{2max}$ they experience soon after arriving at altitude. For acclimatized subjects, the equation expressing this relationship is:

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$$Y = (-1.122)X^2 - (1.8991)X + 99.921 \quad (r^2 = 0.9729) \tag{11}$$

where Y is the percent of $\dot{V}O_{2max}$ measured at sea level and X is the altitude in kilometers (see Fig. 6). This equation predicts a 10.7% decline in $\dot{V}O_{2max}$ for Moser and Ritter at 2338 m versus the 14.7% decline computed for Merckx (using .

The contribution of anaerobic energy sources during an hour record event is probably negligible (1). Thus, we ignored the anaerobic contribution in our calculations, although it would be necessary to consider it in track cycling events of short duration (9). Coyle et al. (12) have shown that highly trained cyclists ($\dot{V}O_{2max}$ = 68.6 mL·kg^{-1}·min^{-1}) can maintain power outputs that are near maximal (89% $\dot{V}O_{2max}$) for approximately 1 h. Hence, we assumed that any decline in $\dot{V}O_{2max}$ with altitude would be accompanied by an equivalent decline in mechanical power output. This is supported by research showing that the efficiency of cycling is unchanged at altitude (33,40) and that fractional utilization of $\dot{V}O_{2max}$ is not impaired (13).

For the hour records set in Mexico City, we took the estimated power outputs and adjusted them upward to reflect the power output of each cyclist at sea level. The estimated sea-level power outputs were then plugged back into the mathematical model. This allowed us to estimate the distance that each cyclist could have covered at sea level, using standardized equipment.

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RESULTS

Table 7 gives an estimate of the power required for previous world hour records from 1967 to 1996. Height and weight for each cyclist are listed along with the correction factors to account for cycling aerodynamic drag. The right-hand column shows the predicted power outputs for each cyclist during his hour record ride, based on the mathematical model we have presented. In the case of Boardman, the power measurements by Peter Keen are used (20,37). In all others, the model was used to predict the power required.

TABLE 7. Power required for cycling 1-h records.

Date	Rider	Height (m)	Mass (g)	Track	Elevation (m)	Distance (km)	Kd	Kp	Kb	Kc	Kh	K1	P (W)
1967	F. Bracke	1.80	72[b]	Rome	48	48.093	0.995	1.08	1.07	1.02	1.04	1.22	400
1968	O. Ritter	1.80	69	Mexico	2338	48.653	0.794	1.08	1.07	1.02	1.04	0.973	336
1972	E. Merckx	1.84	75	Mexico	2338	49.431	0.794	1.08	1.07	1.02	1.04	0.973	366
1984	F. Moser	1.81	78	Mexico	2338	50.808	0.794	1.08	1.0	1.0	1.0	0.858	358
1984	F. Moser	1.81	78	Mexico	2338	51.151	0.794	1.08	1.0	1.0	1.0	0.858	364
1988	F. Moser[a]	1.81	78	Stuttgart	121	50.644[a]	0.988	1.08	0.96	1.0	1.0	1.02	410
1993	G. Obree	1.80	72	Hamar	124	51.596	0.988	0.96	0.93	1.0	1.0	0.882	369
1993	C. Boardman	1.75	68	Bordeaux	73	52.270	0.993	1.0	1.0	1.0	1.0	0.993	409
1994	G. Obree	1.80	72	Bordeaux	73	52.719	0.993	0.95	0.93	1.0	1.0	0.877	389
1994	M. Indurain	1.88	78	Bordeaux	73	53.040	0.993	1.0	0.93	1.0	1.0	0.923	436
1994	T. Rominger	1.75	62	Bordeaux	73	53.832	0.993	1.0	1.0	1.0	1.0	0.993	427
1994	T. Rominger	1.75	62	Bordeaux	73	55.291	0.993	1.0	1.0	1.0	1.0	0.993	460
1996	C. Boardman	1.75	68	Manchester	60	56.375	0.994	0.95	0.93	1.0	1.0	0.878	442

[a] Sea level record in 1988.
[b] Height and weight for Bracke are estimated; values for other cyclists were obtained from published news reports or personal communication.

Power required for cycling 1-h records.

In Table 8 the power outputs have been corrected to sea level, and the distances have been calculated at Manchester using Boardman's equipment (K1 = 0.878). This model predicts that Rominger had the highest power output of all time, based upon his distance 55.291 km and the equipment that he utilized. The estimate of his power is probably somewhat high (460 W), but it should be definitely be greater than Boardman's. Our model estimated Boardman high (452 W), so if one corrects Rominger by the same ratio (442/452), it would give 450 W for Rominger.

TABLE 8. Power and distance, normalized to Manchester, all cyclists using Boardman's equipment and position.

Rider	Track	Elevation (m)	Distance (km)[b]	P (W)[c]	Psl (W)[d]	Dsl[e]
F. Bracke	Rome	48	48.093	400	400	53.2
O. Ritter	Mexico	2338	48.653	336	376	52.4
E. Merckx	Mexico	2338	49.431	366	429	54.0
F. Moser	Mexico	2338	50.808	358	401	52.6
F. Moser	Mexico	2338	51.151	364	407	52.9
F. Moser[a]	Stuttgart[a]	121	50.644	410	410	53.1
G. Obree	Hamar	124	51.596	369	369	51.7
C. Boardman	Bordeaux	73	52.270	409	409	54.3
G. Obree	Bordeaux	73	52.713	389	389	52.7
M. Indurain	Bordeaux	73	53.040	436	436	53.8
T. Rominger	Bordeaux	73	53.832	427	427	55.9
T. Rominger	Bordeaux	73	55.291	460	460	57.0[f]–57.4[f]
C. Boardman	Manchester	60	56.375	442	442	56.4

[a] 1988 sea level record.
[b] Distance, original record distance.
[c] P, power required at the track elevation.
[d] Psl, power corrected to sea level.
[e] Dsl, estimated distance at Manchester, using Boardman's equipment and position K1 = 0.878.
[f] Power, 450 W and 460 W, respectively.

Power and distance, normalized to Manchester, all cyclists using Boardman's equipment and position.

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DISCUSSION

The hour records in Mexico City were characterized by lower power outputs than those at sea level. For the most part, this is due to the decrease in maximal aerobic power at altitude. However, because the Mexico city tracks were outdoors, the riders there may have faced mild wind conditions, causing our estimates of power to be low. Until Moser's sea level record at Stuttgart in 1988, no one had surpassed Bracke in total power output. Moser trained specifically for the hour record (more so than his predecessors) and training methods have continued to improve since then. With Indurain and those following, power outputs increased again.

After adjusting all of the hour records to sea level, using Boardman's latest equipment and position on the bike, some general conclusions can be drawn. Comparing past records on equal terms, the model shows that all of the historic performances until Rominger, would have been reasonably close, 52.4–54.3 km, with Obree's first record (1993) a little lower (51.8 km). Obree's second record (1994) was within the range of the others (52.7 km). Comparing all record holders, we estimate that Rominger would be first, Boardman second, Merckx third, and Indurain fourth. Because Merckx raced outdoors, his 1972 performance is all the more impressive when compared with the recent indoor records.

Some of the older record holders, Merckx, Bracke, Moser, Ritter, and even Indurain, were capable of quite remarkable sea-level power levels for 1 h. The model predicts that all five racers would have been within 1.6 km of each other (52.4–54.0 km), racing under equivalent conditions. Both Boardman and Rominger would have been faster (56 to 57 km).

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Effects of altitude on performance.

Using the present model, the advantage of riding in Mexico City (2338 m) is estimated to be worth 1.68 $km \cdot h^{-1}$, compared with sea level, and for Colorado Springs (1829 m) 1.58 $km \cdot h^{-1}$. In fact, this is similar to the advantage obtained by two cyclists (Francesco Moser and Jeannie Longo) who made hour record attempts in close succession at sea level and altitude using similar equipment (8). The performance advantage in Moser's case was about 1.8 $km \cdot h^{-1}$ when comparing his Mexico City records with those in Milan. Longo derived a 1.5-km advantage in Mexico City (vs Stuttgart and Moscow) and a 1.2-km advantage at the lower elevation of Colorado Springs (vs Milan) (see Table 9).

TABLE 9. Hour records of two cyclists at sea level and altitude.

Date	Cyclist	Location	Distance (km)
1/19/84	F. Moser	Mexico City	50.808
1/23/84	F. Moser	Mexico City	51.151
9/26/86	F. Moser	Milan, Italy	48.544
10/3/86	F. Moser	Milan, Italy	49.802
10/10/87	F. Moser	Moscow, USSR	48.637
5/21/88	F. Moser	Stuttgart	50.644
9/20/86	J. Longo	Colorado Springs	44.770
9/30/86	J. Longo	Milan, Vigorelli	43.586
11/7/86	J. Longo	Grenoble, France	44.718
9/22/87	J. Longo	Colorado Springs	44.933
10/01/89	J. Longo	Mexico City	46.352
10/29/89	J. Longo	Moscow, USSR	45.016
9/29/96	J. Longo	Stuttgart, Germany	46.507
10/26/96	J. Longo	Mexico City	48.159

Sources: 1. UCI Record Book (38); 2. Conconi (11); 3. The Guardian (London) (36).

Hour records of two cyclists at sea level and altitude.

In 1995, Capelli and di Prampero (8) noted that their mathematical model predicted a performance advantage for Moser and Longo that was twice as great as what they actually experienced. A contributing factor to this difference could have been wind on the outdoor tracks of Mexico and Colorado Springs. However, it is likely that the principal difference was due to two factors. First, the tests cited in the present paper show that the mechanical power required to drive a bicycle is a function of the velocity raised to an exponent of about 2.6, whereas it would be a function of the velocity cubed if aerodynamic forces were considered alone. Because Capelli and di Prampero did not have the benefit of crank dynamometers, their model used velocity cubed as a proportionality factor, and thus the model would have overestimated the importance of lower air resistance. A second reason might be that Capelli and di Prampero (8) assumed the $\dot{V}O_{2max}$ decline in Mexico City to be about 8.8%, similar to that reported by Peronnet et al. (30,31). However, in elite athletes the value may be slightly greater than this, even if they are well acclimated.

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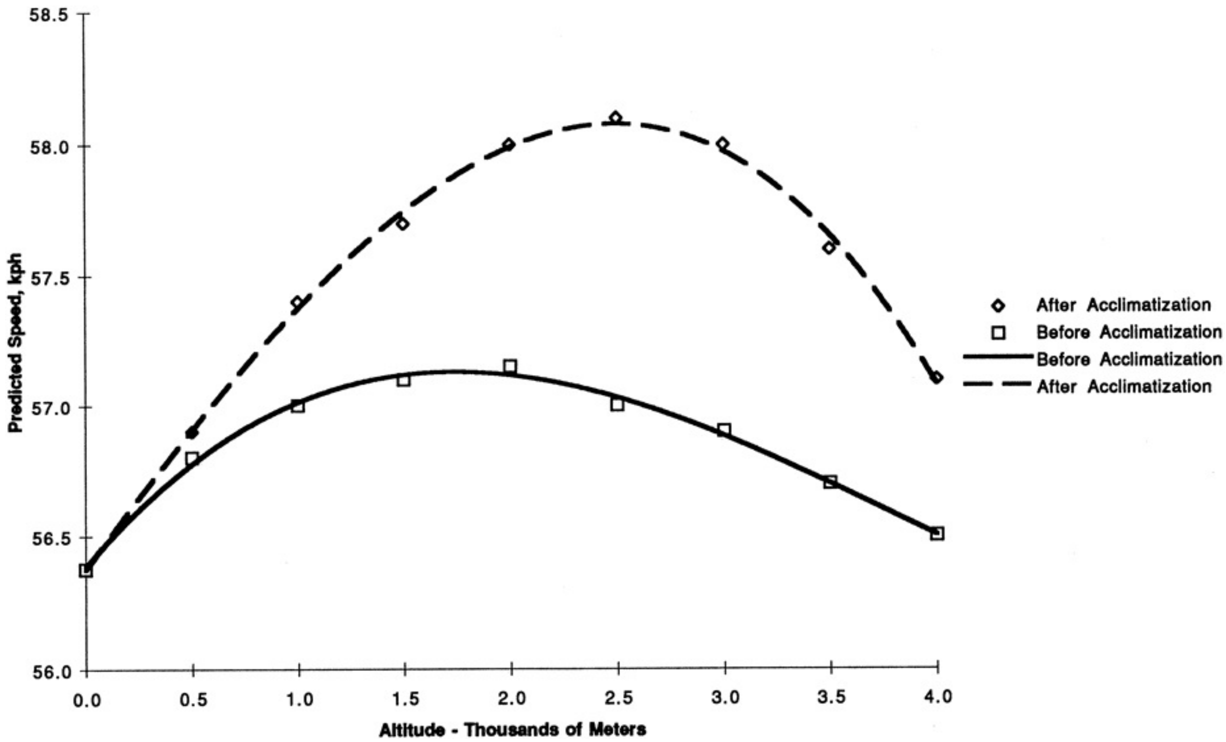
Optimal elevation for hour record attempts.

The optimal elevation for hour record attempts was predicted from the model, with Boardman as the subject, using his latest equipment and the superman position on an indoor track to avoid wind (see Fig. 7). The optimal altitude for Boardman, when acclimatized, would be about 2500 m, where theoretically he could attain a distance of about 58.1 km in 1 h. At higher or lower elevations, his speed would decrease. If he were not acclimatized, then the speed would be about 57.2 $km \cdot h^{-1}$ at an optimal elevation of about 2000 m. Coincidentally, these two elevations bracket Mexico City (2338 m); so, according to our model, there would be little reason to attempt the hour record at a higher elevation. The theoretical optimal elevation of 2500 m is less than reported by other investigators. Peronnet and coworkers (30,31) predict about 4000 m as being optimal as do Capelli and di Prampero (8). That elevation is slightly higher than the altitude of the Alto Irpavi velodrome (La Paz, Bolivia, 3658 m), where Capelli and di Prampero estimate that Rominger's performance would equal 60.1 $km \cdot h^{-1}$ (8). Our model predicts that Rominger's distance would be about 1.5 km less than this at La Paz.



The theoretical distance Christopher Boardman could cycle in 1 h at various elevations. The upper curve assumes Boardman is acclimated and reaches a maximum of 58.1 km at about 2500 m. The lower curve assumes Boardman has not trained at altitude and reaches a maximum of 57.2 km at about 2000 m.

It is interesting to compare the theoretical performances of Rominger and Boardman at Mexico City and La Paz, Bolivia, on an indoor track. In theory, at Mexico City (2338 m), Rominger and Boardman should be able to go about 59.1 km (411 W) and 58.1 km (395 W) respectively. At La Paz, Bolivia (estimated elevation of 3658 m), they should go about 58.6 km (359 W) and 57.5 km (345 W), which is greater than they could manage at sea level but less than at Mexico City.

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Limitations of the model.

The model’s estimate of power seems to be accurate to within an absolute error of about 4%. So power figures within about 4% of each other can be considered equivalent. In estimating the elapsed time to go a certain distance, the absolute error would be less, about 1.6%. However, even after attempting to account for as many factors as possible, it is apparent that generalized models have their limitations. On the other hand, specific SRM tests can be used to predict performance very accurately, provided a reliable measure of the cyclist's endurance power potential is available (ergometer data, field performance data, $\dot{V}O_{2max}$ data).

Another limitation to the model, is the considerable variability between individuals for the percent decline in $\dot{V}O_{2max}$ at altitude. For each of the studies shown in Figure 6, the standard deviations are about 5%. The average percent decline in $\dot{V}O_{2max}$ in Mexico City is 14.7% for unacclimatized athletes. This means that two-thirds of the athletes will experience a decrease between 9.7% and 19.7% (14.7 ± 5%). The entire range in $\dot{V}O_{2max}$ decrement for all three studies done in Mexico City was from 4.6% to 25.1% (13,17,33). Further, J. T. Kearney of the USOC Sports Sciences (personal communication, August, 1998) found that Lance Armstrong, the former professional road race champion, showed no decline in $\dot{V}O_{2max}$ at the elevation of Colorado Springs (1829 m). Thus, even though one can predict the decline in power output that Ritter, Merckx, and Moser might have experienced in Mexico City, it is uncertain how any particular cyclist would respond to 2300-m elevation. However, by estimating the $\dot{V}O_{2max}$ decline on the basis of studies of highly trained athletes, one can improve on the statistical accuracy of prediction.

In summary, by using field crank dynamometer measurements, the present study extended the mathematical modeling approach used in previous studies that compare hour record performances. After adjusting for differences in altitude and aerodynamic factors between cyclists, several conclusions can be drawn. The earlier record holders who used traditional round tube track bicycles (Bracke, Ritter and Merckx) averaged sea level powers of about 402 W. However, Merckx's 1972 performance (429 W) stands out above the others. The next series of record holders, who all used various aerodynamic improvements (Moser, Boardman, Obree) averaged sea level powers of about 403 W, or about the same. The aerodynamic improvements during this era resulted in a record distance increase of about 10%. The last three challengers (Indurain, Rominger, and Boardman) averaged 446 W, a large increase in power compared with the previous record holders. During this period, the available bicycle aerodynamic improvements did not change as markedly. The increased power of these cyclists, resulted in a distance increase of about 7%. In other words, since Bracke's era, about 60% of the improvement in the hour record distance has come from aerodynamic advances and about 40% from higher power outputs. The combination has produced the recent meteoric rise in the hour record. Finally, future hour records at altitude should be possible, especially if the current champions use indoor velodromes at higher elevations, where the conditions of the track are constant.

The authors express their appreciation to Lana Dixon and Chris Pelton for assistance with locating references needed for the study.

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