Level ground and uphill cycling ability in professional road cycling

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ABSTRACT

PADILLA, S., I. MUJIKA, G. CUESTA, and J. J. GOIRIENA. Level ground and uphill cycling ability in professional road cycling. *Med. Sci. Sports Exerc.*, Vol. 31, No. 6, pp. 878–885, 1999. **Purpose:** To evaluate the physiological capacities and performance of professional road cyclists in relation to their morphotype-dependent speciality. **Methods:** 24 world-class cyclists, classified as flat terrain (FT, $N = 5$), time trial (TT, $N = 4$), all terrain (AT, $N = 6$), and uphill (UH, $N = 9$) specialists, completed an incremental laboratory cycling test to assess maximal power output (W_{max}), maximal oxygen uptake ($\dot{V}O_{2max}$), lactate threshold (LT), and onset of blood lactate accumulation (OBLA). **Results:** UH had a higher frontal area (FA):body mass (BM) ratio ($5.23 \pm 0.09\ m^2 \cdot kg^{-1} \cdot 10^{-3}$) than FT and TT ($P < 0.05$). FT showed the highest absolute W_{max} (481 ± 18 W), and UH the highest W_{max} relative to BM ($6.47 \pm 0.33\ W \cdot kg^{-1}$). W_{LT} and W_{OBLA} values were significantly higher in FT (356 ± 41 and 417 ± 45 W) and TT (357 ± 41 and 409 ± 46 W) than in UH (308 ± 46 and 356 ± 41). Scaling of these values relative to FA and BM exponents 0.32 and 0.79 minimized group differences, but considerable differences among mean group values remained. FT and TT had the highest W_{max} per FA unit (1300 ± 62 and $1293 \pm 57\ W \cdot m^2$), whereas TT had the highest absolute $W \cdot kg^{-0.32}$ and $W \cdot kg^{-0.79}$, as well as $W \cdot kg^{-0.32}$, $W \cdot kg^{-0.79}$, and $W \cdot m^{-2}$ at the LT and OBLA. **Conclusions:** i) Scaling of maximal and submaximal physiological values showed a performance advantage of TT over FT, AT, and UH in all cycling terrains and conditions; and ii) mass exponents of 0.32 and 1 were the most appropriate to evaluate level and uphill cycling ability, respectively, whereas absolute W_{max} values are recommended for performance-prediction in short events on level terrain, and W_{LT} and W_{OBLA} in longer time trials and uphill cycling. **Key Words:** POWER OUTPUT, OXYGEN UPTAKE, SCALING, BODY DIMENSIONS, ONSET OF BLOOD LACTATE ACCUMULATION, LACTATE THRESHOLD

From a metabolic viewpoint, road cycling is an endurance sport with very high aerobic demands. Indeed, high maximal oxygen uptake (2,8,10,21,27) and power output values at the lactate threshold have often been reported among competitive road cyclists under laboratory conditions (2,3,12,17). However, it has been suggested that, for a more accurate prediction of the cyclist's performance level in the field, physiological values obtained in the laboratory should be expressed relative to anthropometric variables, because of their influence on road cycling performance (20–22,31).

Indeed, road cycling is a sport that requires performing in a great variety of terrains (e.g., level or uphill roads) and competitive situations (e.g., individual cycling or drafting at the back of a group of cyclists in pack formation). In any of the above-mentioned situations, the amount of work performed by a cyclist is determined to a great extent by anthropometric variables (6,31,32). These include body mass and frontal area, which are among the most important performance-determining anthropometric variables, as the former determines gravity-dependent resistance, having thus a major influence on uphill cycling performance, whereas the latter affects performance during individual time trials, due to its influence on aerodynamic resistance (6,32). Therefore, a road cyclist's performance on each type of terrain is conditioned by his morphological characteristics. This has contributed to the appearance of morphotype-dependent specialists in professional cycling, with clearly defined roles during the different phases of a race.

It is evident, however, that to win a 3-wk stage race such as the Tour de France, a cyclist must be competitive during all phases of the race (i.e., level, uphill and downhill terrain, and individual time trials). This requires the best possible compromise between the cyclists' physiological and morphological characteristics on the one hand and the competitive demands of the race on the other hand.

Several investigations have studied the relationships between metabolic and anthropometric variables during bicycling (3,6,16,22,31,32). Until now, however, no study has analyzed separately these relationships with regard to the cyclist's main specific role in competition. It was thus the purpose of this study to evaluate the physiological capacities and performance of professional road cyclists, in relation to their morphotype-dependent speciality during stage races.

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METHODS

Subjects. Twenty-four members of a professional road cycling team participated in this study. All of them were competing at an international level and had raced at least once in the Tour de France. Three of the cyclists were 3-wk stage race winners (Tour de France, Giro d'Italia, and Vuelta a España), adding up a total of nine victories, whereas three other cyclists were runner-ups in these races. Subject characteristics are listed in Table 1. Cyclists were tested in April, that is, during their competitive season. At the time of testing, they had already cycled approximately 10,000 km in training and competition since the beginning of the season and were currently cycling 700–1000 km·wk^{-1}. Based on the recommendation of the team coach, and according to their role in competition, cyclists were included in one of five possible groups: uphill riders (UH, $N = 9$), i.e., cyclists who perform their team work mainly in the hills; flat terrain riders (FT, $N = 5$), i.e., cyclists who contribute to the control of the race mainly on level roads; all terrain riders (AT, $N = 6$), who can perform fairly well in all kinds of terrains; time trial specialists (TT, $N = 4$), who are able to achieve outstanding individual performances in the time trial stages; and sprinters, i.e., those riders who mainly race for the win in level road stages. None of the riders of this study were sprinters, because the main goal of the team was not to achieve stage wins but rather the overall victory in 3-wk stage races. Subjects gave their written informed consent to participate after verbal and written explanation of the purpose, procedures, and potential risks of the study. All experimental procedures were approved by the ethics committee of the Instituto Vasco de Educación Física.

Anthropometric variables. Body surface area (BSA, in m^2) was determined from each cyclist's body mass and height, as described by Du Bois and Du Bois (7):

$$BSA = 0.007184 \cdot BM^{0.425} \cdot H^{0.725}$$

in which BM is body mass (in kg), and H is the height of the cyclist (in cm).

Assuming that frontal area (FA) can be considered proportional to BSA (6), and based on previously measured values (21,32), the value of FA was considered to be 18.5% of BSA.

Scaling of maximal and submaximal aerobic power and oxygen uptake values was performed using mass exponents of 0.32 to evaluate level cycling ability and 0.79 to evaluate uphill cycling ability (31).

TABLE 1. Subject characteristics.

	Mean ± SD	Range
Age (yr)	26 ± 3	20 – 33
Height (cm)	180 ± 6	160 – 190
Mass (kg)	68.2 ± 6.6	53.0 – 80.0
W_{max} (W)	431 8 ± 42 6	349 – 525
W_{max} (W·kg^{-1})	6 34 ± 0.30	5 58 – 6.82
$\dot{V}O_{2max}$ (L·min^{-1})	5.36 ± 0 47	4.42 – 6.42
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	78.8 ± 3.7	69.7 – 84 8
HR_{max} (beats·min^{-1})	192 ± 6	178 – 204
La_{max} (mmol·l^{-1})	9.8 ± 1.9	6.9 – 13.7

N = 24 subjects. W_{max}, maximal power output; $\dot{V}O_{2max}$, maximal oxygen uptake; HR_{max}, maximal heart rate; La_{max}, maximal blood lactate concentration.

Protocol. All cyclists performed a rectangular incremental maximal laboratory test on a mechanically braked cycle ergometer (Monark 818 E, Varberg, Sweden) adapted with a racing saddle, drop handlebars, and clip-in pedals. Initial resistance was set at 110 W and was increased by 35 W every 4 min, with 1-min recovery intervals between workloads. Pedal rate was maintained constant at 75 rpm throughout the test. Subjects kept cadence with a metronome. Testing continued until the subjects were no longer able to maintain the required pedal rate. The ergometer was placed on a perfectly level floor, and a calibration was performed using 2- and 5-kg weights before each test. Blood samples were obtained immediately after completion of each workload for blood lactate concentration (BL) determination. BL values attained during the last workload maintained for at least 2 full minutes were considered as maximal. Heart rate was recorded throughout the test (Sport Tester PE3000, Polar Electro, Kempele, Finland).

Maximal power output. It was determined as the highest workload a cyclist could maintain for a complete 4-min period. When the last workload was not maintained 4 full minutes, maximal power output (W_{max}) was calculated as follows (13):

$$W_{max} = W_f + (t/240) \cdot 35$$

in which W_f is the value of the last complete workload (W), t is the time the last workload was maintained (s), and 35 is the power output difference between the last two workloads (W).

Maximal oxygen uptake. To avoid any possible interference of gas analyzing equipment with the subject's cycling performance, $\dot{V}O_{2max}$ (in L·min^{-1}) was estimated from W_{max}, using the regression equation proposed by Hawley and Noakes (10):

$$\dot{V}O_{2max} = 0.01141 \cdot W_{max} + 0.435$$

Blood lactate. Capillary blood samples (25 μL) were withdrawn from a previously hyperemized ear lobe during the first recovery seconds after each workload. BL concentration was immediately determined by an electroenzymatic technique with an automatic analyzer (YSI® 1500 Sport, Yellow Springs Instruments, Yellow Springs, OH). Before each incremental test, the analyzer was calibrated with standard solutions of known lactate concentrations (0, 5, and 15 mmol·L^{-1}), as recommended by the manufacturer.

LT and OBLA determination. The lactate threshold (LT) was identified on each subject's BL concentration-power output curve as the exercise intensity that elicited a 1 mmol·L^{-1} increase in BL concentration above average baseline lactate values measured when exercising at 40–60% of $\dot{V}O_{2max}$ (9). The onset of BL accumulation (OBLA) was identified on the BL concentration-power output curve as the exercise intensity eliciting a BL concentration of 4 mmol·L^{-1} (26).

Statistical analyses. Descriptive statistics are expressed as means ± SD. ANOVA, followed by Fisher's *post hoc* test, was used to study differences among groups. The level of statistical significance was set at $P < 0.05$. Additionally, group differences for power output and oxygen uptake variables were expressed as a percentage of change relative to the highest value of the two groups being compared.

RESULTS

Anthropometric variables. The main anthropometric characteristics of each group of cyclists are presented in Table 2. UH were significantly lighter, had lower BSA and FA, but higher $BSA \cdot BM^{-1}$ than all other groups. Moreover, UH also had significantly higher $FA \cdot BM^{-1}$ values than FT and TT, in addition to being shorter than FT. AT were also significantly lighter, had smaller BSA and FA, and higher $BSA \cdot BM^{-1}$ and $FA \cdot BM^{-1}$ than FT.

Maximal power output. The highest absolute W_{max} values were measured in FT (461 ± 39 W), this value being higher than that of AT (432 ± 27 W) and UH (404 ± 34 W, $P < 0.05$). TT also showed a significantly higher W_{max} value (457 ± 46 W) than UH (Fig. 1, A). When expressed relative to body mass, UH presented the highest W_{max} (6.47 ± 0.33 $W \cdot kg^{-1}$), followed by TT, AT, and FT (6.41 ± 0.12, 6.35 ± 0.18 and 6.04 ± 0.29 $W \cdot kg^{-1}$, respectively). These values were significantly different between UH and FT (Fig. 1, B).

Even though rather large variations existed among groups in the mean values of W_{max} relative to mass exponents of 0.32 and 0.79, as well as relative to the cyclists' frontal area, these differences did not reach the level of statistical significance (116.6 ± 8.6, 115.0 ± 8.5, 111.9 ± 5.6, 107.6 ± 7.3 $W \cdot kg^{-0.32}$, 15.69 ± 0.54, 14.99 ± 0.80, 15.40 ± 0.57, 15.43 ± 0.80 $W \cdot kg^{-79}$, and 1,293 ± 57, 1,300 ± 62, 1,253 ± 51, 1,239 ± 66 $W \cdot m^{-2}$ for TT, FT, AT, and UH, respectively).

Percentage differences in absolute and relative power output values among groups are shown in Figure 2. Some of these differences reached values of up to 7.7%, although they were statistically nonsignificant.

Maximal oxygen uptake. As shown in Figure 3A, estimated absolute $\dot{V}O_{2max}$ values were significantly higher in FT (5.67 ± 0.44 $l \cdot min^{-1}$) and TT (5.65 ± 0.53 $l \cdot min^{-1}$) than in UH (5.05 ± 0.39 $l \cdot min^{-1}$), but none of these were significantly different from AT (5.36 ± 0.30 $l \cdot min^{-1}$). $\dot{V}O_{2max}$ relative to body mass (Fig. 3, B), on the other hand, was significantly lower in FT (74.4 ± 3.0 $mL \cdot kg^{-1} \cdot min^{-1}$) than in TT, AT, and UH (79.2 ± 1.1, 78.9 ± 1.9 and 80.9 ± 3.9 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively).

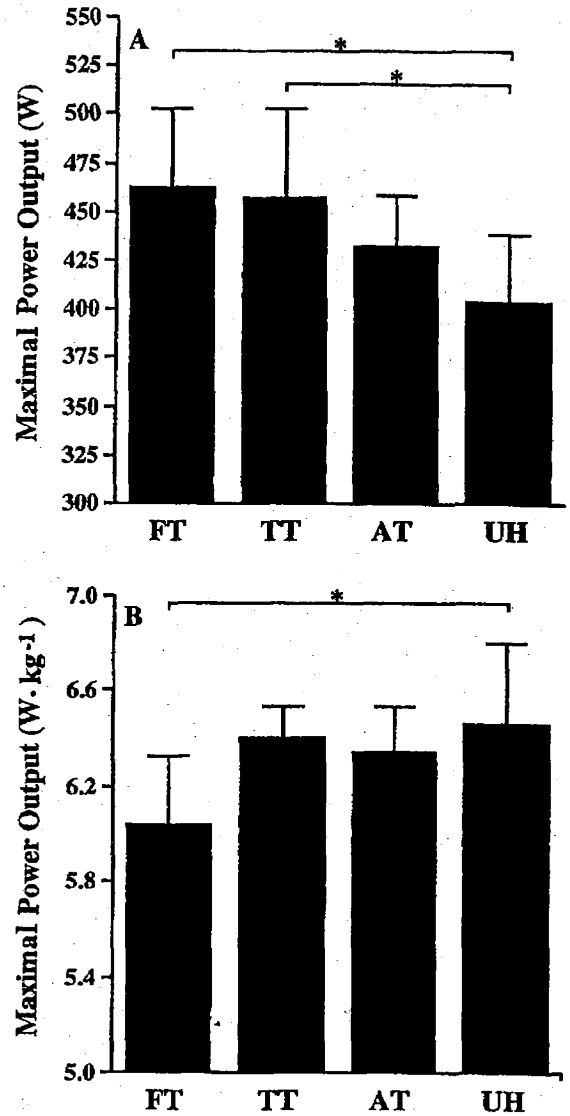
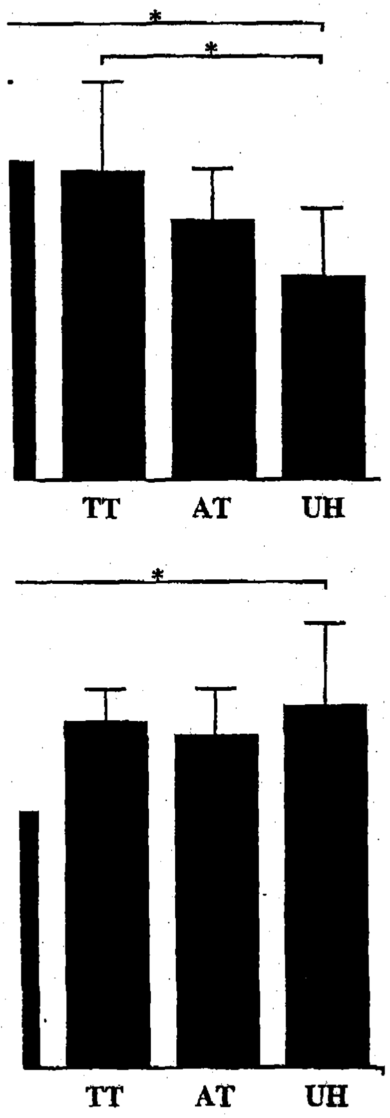


Figure 1—Mean ± SD. Maximal power output values for flat terrain (FT, $N = 5$), time trial (TT, $N = 4$), all terrain (AT, $N = 6$), and uphill (UH, $N = 9$) specialists. A: absolute values; B: relative to body mass. * denotes a significant difference ($P < 0.05$) between groups.

TABLE 2. Group anthropometric characteristics.

	FT ($N = 5$)	TT ($N = 4$)	AT ($N = 6$)	UH ($N = 9$)
Age (yr)	27 ± 3	28 ± 5	25 ± 2	25 ± 4
Height (cm)	186 ± 4	181 ± 6	180 ± 2	175 ± 7*
Mass (kg)	76 2 ± 3.2	71.2 ± 6.0	68.0 ± 2.8*	62.4 ± 4 4*†‡
BSA (m^2)	2.00 ± 0.06	1.91 ± 0 11	1.87 ± 0.04*	1.76 ± 0.10*†‡
FA (m^2)	0.370 ± 0.011	0.353 ± 0.020	0.345 ± 0.008*	0 326 ± 0.019*†‡
$BSA \cdot BM^{-1} \cdot 10^{-3}$	26 26 ± 0.48	26.82 ± 0.73	27.44 ± 0.53*	28 27 ± 0.49*†‡
$FA \cdot BM^{-1} \cdot 10^{-3}$	4.86 ± 0.09	4.96 ± 0 13	5.07 ± 0.10*	5.23 ± 0.09*†

Values are means ± SD. FT, flat terrain specialists; TT. time trial specialists; AT. all terrain riders; UH, uphill specialists: BSA, body surface area; FA, frontal area; BM, body mass; *, significantly different from FT, †, significantly different from TT. ‡, significantly different from AT.



Maximal power output values for flat terrain

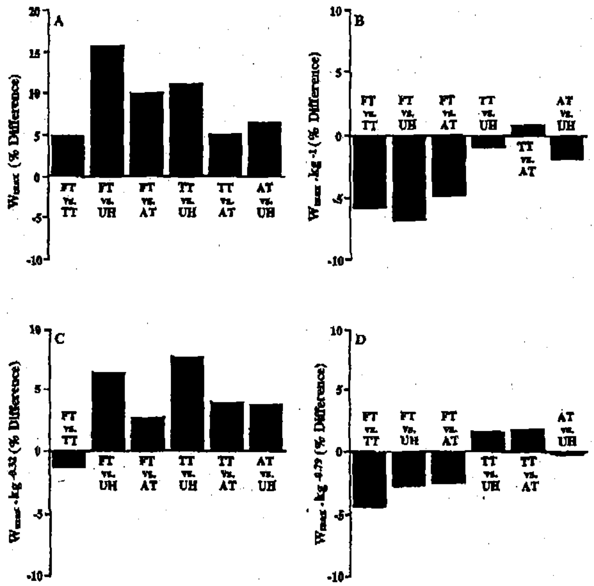


Figure 2—Percentage differences in mean maximal power output (W_{max}) values among flat terrain (FT, $N = 5$), time trial (TT, $N = 4$), all terrain (AT, $N = 6$), and uphill (UH, $N = 9$) specialists. A: absolute values; B: relative to body mass; C: relative to body mass exponent of 0.32; D: relative to body mass exponent of 0.79.

Percentage differences in estimated absolute and relative oxygen uptake values among groups ranged between 0.3 and 11%.

Blood lactate. Maximal BL concentration values measured during the incremental test were 9.3 ± 1.2, 9.3 ± 2.7, 11.1 ± 1.8, and 9.5 ± 1.9 mmol·L^{-1} for FT, TT, AT, and UH, respectively, not being significantly different among groups.

Power output at LT and OBLA. Absolute and relative power output values at the LT and OBLA exercise intensities are shown in Tables 3 and 4, respectively. At LT, the highest absolute power output corresponded to TT, followed by FT, AT, and UH. FT had the highest values at OBLA, followed by TT, AT, and UH, the values of FT and TT being

indicated by their mean W_{max} both in absolute values (431.8 W) and in relation to body mass (6.34 W·kg^{-1}). These values were higher than most previously reported values for competitive road cyclists (3,14,27), most likely due to the higher competitive level of the cyclists in the present study (Table 5). Indeed, the term "elite" has often been used in the literature in reference to road cyclists of a wide range of competitive levels. As previously mentioned, cyclists participating in this investigation were all professional and had participated in the races for the true "elite" of road cycling (Tour de France, Giro d'Italia, and Vuelta a España), achieving outstanding results.

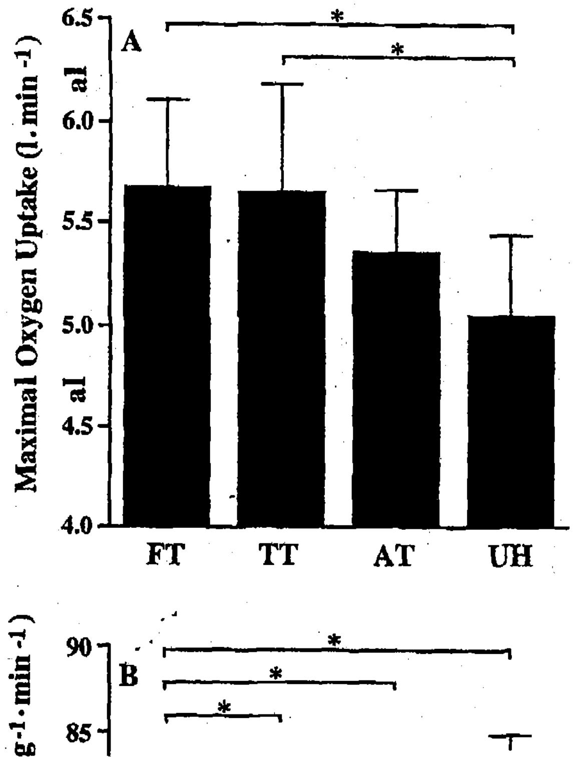


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TABLE 3 Absolute and relative power output values at the individual lactate threshold.

	FT (N = 5)	TT (N = 4)	AT (N = 6)	UH (N = 9)
W_{LT} (W)	356 ± 31	357 ± 41	322 ± 43	308 ± 46
W_{LT} ($W \cdot kg^{-1}$)	4.67 ± 0.25	5.00 ± 0.20	4.73 ± 0.48	4.91 ± 0.50
W_{LT} ($W \cdot kg^{-0.32}$)	89.0 ± 6.7	91.0 ± 8.0	83.4 ± 10.0	81.9 ± 10.8
W_{LT} ($W \cdot kg^{-0.79}$)	11.60 ± 0.69	12.25 ± 0.64	11.47 ± 1.23	11.71 ± 1.29
W_{LT} ($W \cdot m^{-2}$ FA)	962.5 ± 59.0	1,009.7 ± 65.0	933.7 ± 110.2	940.7 ± 10.3
W_{LT} (%W_{max})	77 ± 2	78 ± 3	74 ± 7	76 ± 3

Values are means ± SD. FT, flat terrain specialists; TT, time trial specialists; AT, all terrain riders; UH, uphill specialists; W_{LT}, power output at the individual lactate threshold; FA, frontal area. All group differences were nonsignificant.

Power outputs as high as 470 W (36), 457 W (34), and even 575 W (17) have also been reported in the literature (Table 5). These extremely high average values can most probably be attributed to the shorter duration of the increments used by the above mentioned authors (i.e., 2–3 min, and even 1 min at power outputs approaching W_{max}), in comparison with the 4-min increments used in the present study, which can result in higher power outputs, both at maximal and submaximal exercise intensities (5,35,37). Moreover, the type of cycle ergometer used during testing should also be taken into consideration, as power output values obtained on mechanically braked cycle ergometers (e.g., Monark ergometers) are 9% lower than values obtained on electromagnetically braked ergometers, due to the lack of friction in the transmission system of the latter (1). Under these conditions, the estimated W_{max} of the present group of cyclists would have been quite similar to some of the above-mentioned values (i.e., 470.7 W), in spite of the much longer work intervals.

It has been suggested that a power output:body mass ratio above 5.5 $W \cdot kg^{-1}$ is a necessary prerequisite for top-level competitive cyclists (24). However, this suggested value is not intended for professional cyclists. Indeed, this value seems to be slightly low for professional cycling, according with the present (mean value of 6.34 $W \cdot kg^{-1}$, with a lowest value of 5.58 $W \cdot kg^{-1}$) and previously reported data (Table 5). Ice et al. (12) described a power output:body mass ratio of 6.79 $W \cdot kg^{-1}$ for the several-time winner of the race across America.

As oxygen uptake was not directly measured in this study, the results concerning this variable will not be discussed in depth. However, it is worth noticing that estimated values of the present group of cyclists (i.e., 5.36 $l \cdot min^{-1}$ and 78.8 $mL \cdot kg^{-1} \cdot l^{-1}$) were comparable to those of other cycling populations previously studied (Table 5) and of athletes participating in events with high aerobic demands, such as long-distance running (5000 m, 10,000 m, and marathon). These values were indeed very similar to those reported by Noakes (19), Saltin et al. (25), and Svedenhag and Sjödin (30) for international level endurance runners.

It is clear that anthropometric characteristics play a major role in the resistance a cyclist must overcome to generate movement. Taking this into consideration, various authors have developed mathematical equations to estimate cycling performance based upon physiological and physical variables (6,20,21). Moreover, it has been suggested that physiological measures obtained under laboratory conditions should be expressed relative to body mass, body surface area, or frontal area, to avoid the interaction between physiological characteristics and body dimensions and thus obtain a more accurate prediction of the cyclist's performance on the road (18,22,29,31). Therefore, scaling of physiological variables should allow to compare subjects with different body dimensions (which determine specific roles in professional cycling teams) and to evaluate their physiological and performance potential independent of body size.

As shown by the present results, scaling of physiological variables such as maximal and submaximal power output or $\dot{V}O_{2max}$ minimized the differences between groups, which were quite considerable when those variables were expressed in absolute terms. This observation suggests that absolute power output and oxygen uptake differences between groups can be attributed to the cyclists' morphological characteristics, even though the groups of specialists were determined attending to the empirical criterion of the team coach. UH showed the lowest BM of all groups. A low BM has been considered to give an edge over heavier competitors in uphill races implying a lower velocity and thus minimizing the influence of aerodynamic resistance on the total amount of work (6,31). The bigger and heavier cyclists included in the groups FT and TT, on the other hand, have some other advantages over UH, such as lower $BSA \cdot BM^{-1}$ and $FA \cdot BM^{-1}$ ratios. Indeed, these variables have been related with a lower aerodynamic resistance in relation to BM, resulting in a lower energy cost per unit of BM (32). Moreover, height and body size have been shown

TABLE 4. Absolute and relative power output values at the onset of blood lactate accumulation.

	FT (N = 5)	TT (N = 4)	AT (N = 6)	UH (N = 9)
W_{OBLA} (W)	417 ± 45	409 ± 46	366 ± 38	356 ± 41*†
W_{OBLA} ($W \cdot kg^{-1}$)	5.46 ± 0.42	5.73 ± 0.21	5.37 ± 0.37	5.70 ± 0.46
W_{OBLA} ($W \cdot kg^{-0.32}$)	104.1 ± 10.3	104.3 ± 8.9	94.8 ± 8.7	94.8 ± 9.6
W_{OBLA} ($W \cdot kg^{-0.79}$)	13.57 ± 1.10	14.03 ± 0.69	13.04 ± 0.99	13.57 ± 1.14
W_{OBLA} ($W \cdot m^{-2}$ FA)	1,125.8 ± 100.3	1,156.8 ± 70.0	1,061.0 ± 91.0	1,090.4 ± 88.0
W_{OBLA} (%W_{max})	90 ± 3	89 ± 2	84 ± 5	88 ± 5

Values are means ± SD. FT, flat terrain specialists; TT, time trial specialists; AT, all terrain riders; UH, uphill specialists; W_{OBLA}, power output at the onset of blood lactate accumulation; FA, frontal area. *, significantly different from FT; †, significantly different from TT

TABLE 5. *Physical characteristics, maximum power output and maximum oxygen uptake of cyclists.*

Reference	Cycling Level	Height (cm)	Mass (kg)	Ergometer Brake	W_{max} (W)	W_{max} ($W \cdot kg^{-1}$)	$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)
Coyle et al. (3)	Elite		72.8	Mechanical	406*	5.58*	5.07*	69.1*
Hopkins and McKenzie (11)	Amateur	185	75	Electromagnetic	405*	5.39*	5.05*	68.0*
Lacour et al. (14)	Professional	179	72.0	Mechanical	411	5.71	5.12	70.1
Lindsay et al. (15)	Amateur	182	79.1	Electromagnetic	416	5.26	5.20	65.7
Padilla et al. (22)	Amateur	178	67.9	Mechanical	365	5.37	4.49	66.1
Palmer et al. (24)	Amateur		74.5	Electromagnetic	398	5.39	4.97	66.7
Palmer et al. (23)	Amateur	181	77.6	Air	443	5.71	5.48	73.6
Present study	Professional	180	68.2	Mechanical	432	6.34	5.36	78.8
Sjøgaard (27)	Professional	178	71.0	Mechanical	397*	5.58*	4.96*	71.0*
Strømme et al (28)	Elite		80.1		447*	5.57*	5.53*	69.1*
Tanaka et al. (33)	Amateur	179	71.8	Mechanical	398*	5.55*	4.98*	69.4*
Terrados et al. (34)	Professional	179	71.0	Mechanical	428†	6.03†	5.04†	70.0
Wilber et al. (36)	Elite	182	72.6	Electromagnetic	470	6.50	5.09	79.3

Values are means; W_{max}, maximum power output; $\dot{V}O_{2max}$, maximum oxygen uptake. *, values estimated using the regression equation of Hawley and Noakes (10); †, average values of the two groups of cyclists reported in the reference.

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to be positively related with a 26-km time trial performance (21).

Several authors (10,15,23) have found significant relationships between peak mechanical power attained in the laboratory and 20- to 40-km individual time trial performance on the road, reporting r values ranging between 0.84 and 0.99. Moreover, laboratory W_{OBLA} and W_{LT} have also been related with 40-km (3,11) and 26-km (4) time trial performance. According to these results, FT cyclists should have been the best time trial riders, as they showed higher absolute W_{max} and W_{OBLA} values than TT, AT and UH, as well as W_{LT} values equal to those of TT and well higher than AT and UH.

However, using the data reported by Coyle et al. (3), Swain (31) showed the influence of scaling on cycling performance. Indeed, this author observed a higher correlation between the average power output during 1-h laboratory cycling and a 40-km time trial on the road when the former variable was expressed relative to a mass exponent of 0.32 ($r = -0.88$ vs $r = -0.94$, respectively). This observation led him to suggest that this mass exponent should be used to normalize physiological values obtained under laboratory conditions to better predict performance on the road. This suggestion was validated by the present results. Indeed, relative to the mass exponent 0.32, TT showed higher average W_{max}, W_{OBLA}, and W_{LT} values than the other groups of specialists, FT included. Due to respectively high power values relative to the mass exponent 0.32 and to an excellent $W_{max} \cdot FA^{-1}$ ratio, TT and FT usually got better competition placing in individual time trials and indoor cycling than AT and UH.

Two remarks could be made concerning cycling performance in competitive time trials: i) in the 3-wk race opening time trials (i.e., "prologue" stage), which are most often performed on level terrain and last 6–15 min, better performances are usually achieved by cyclists who could be considered as time trial specialists and flat terrain riders. Professional cyclists including Indurain, Zulle, Nijdam, Marie, Moreau, Mauri, and Boardman (two of whom were included in the TT group of the present study) have reached the top positions in this type of race in the last few years. This is indicative of the performance-predicting validity of variables such as $W \cdot kg^{-0.32}$ and $W \cdot m^{-2}$ for flat, short-duration time trials; ii) in the longer individual time trials, during which exercise intensity is close to LT (4) or OBLA (3,11,23), TT have an edge over the rest of cyclists, as they showed the highest submaximal power output values relative to both mass exponent 0.32 and FA. This is indeed usually reflected by competition placing. Differences between TT and FT, however, have probably more to do with the facts that these stages are hardly ever raced on level roads and that FT often do not perform at their highest possible level due to team tactics and race strategies, than with actual differences in physiological potential. Differences between TT and UH, on the other hand, mainly depend on the type of terrain (level or uphill) and the air resistance, as smaller cyclists are disadvantaged when the resistance they must overcome is mainly that of air (level ground) rather than that due to the force of gravity (uphill), due to their much higher $FA \cdot BM^{-1}$ ratio (32).

Road cycling is a sport mainly performed at submaximal intensities. As previously indicated, individual time trials lasting between 15 and 60 min are raced at intensities close to OBLA. Group stages often require cycling uphill for 30–90 min, three to seven times, also at intensities close to LT and OBLA. Therefore, scaling mechanical power output at these submaximal intensities appears to be also necessary to appreciate performance potential during uphill cycling. It is worth noticing that in this study, TT showed higher W_{LT} and W_{OBLA} relative to body mass and to body mass exponent 0.79 than all other specialists, including UH. This finding was supported by race results, as TT repeatedly excelled when performing uphill. The choice of the appropriate mass exponent for a best prediction of uphill cycling performance is a controversial issue. Swain (31) suggested that this could be 0.79 but stated that this value was not as well established as the 0.32 mass exponent for level cycling. Other authors (29) have suggested a similar value (0.75) for running, during which BM has a major influence on performance because of its effects on gravity-induced resistance. This is also the case during uphill cycling, but the incline of the terrain being much higher, the mass exponent 1 (i.e., body mass) seems to be more appropriate to express both $\dot{V}O_{2max}$ and W_{max} (18). Indeed, when the mass exponent 1 was used in this study, UH showed the highest $W_{max} \cdot kg^{-1}$ values of all groups of specialists. This is reflected in actual competition by the higher accelerating capacity shown by this type of cyclists in the hills during group stages. Top level performances in uphill time trials usually achieved by UH could also be explained by their high $W_{LT} \cdot kg^{-1}$ and $W_{OBLA} \cdot kg^{-1}$, very similar to those of TT. These observations indicate that UH and TT have a similar aptitude in uphill cycling, which is corroborated by analyzing the results of mountain stages during 3-wk races of the last few years: small, light cyclists (e.g., Pantani, Virenque, Chiapucci, and Ugrumov) have shared the top positions with bigger, heavier cyclists (e.g., Indurain, Zulle, Riis, and Ullrich).

Scaling of physiological capacities indicated the overall performance advantage of TT in comparison with the other groups of specialists, i.e., FT, AT, and UH. Most group differences, however, did not reach the level of statistical significance. This observation leads to the following considerations concerning sports performance in general and road cycling performance in particular: i) performance is a singular event depending on a multiplicity of variables and circumstances. Thus, in addition to the above discussed physiological and morphological characteristics, road cycling performance is also determined by other variables, such as thermoregulatory, recovery and psychological capacities, health condition, or race strategy, which have not been studied in the present investigation; ii) 3-wk stage races are usually won or lost by time differences ranging between 200 and 400 s, representing 0.07–0.13% of an overall time of about 300,000 s. Because of their influence on competition placing, these differences, which are insignificant from a statistical point of view, are of major importance from an athletic point of view.

In conclusion, scaling of physiological capacities indicated that TT had an overall performance advantage over the other groups of specialists in all types of cycling terrains (i.e., level or uphill) and riding conditions (i.e., individually or in pack formation). Though these differences alone cannot completely explain performance differences and competition placing in 3-wk stage races, the present results showed that scaling of maximal and submaximal physiological values is a valuable approach to evaluate road cycling performance. Mass exponents of 0.32 and 1 are suggested to evaluate level and uphill cycling ability, respectively. Absolute W_{max} values are recommended for prediction of performance in short events on level terrain such as opening time trials, whereas values at LT and OBLA appear to be more appropriate for longer time trials and uphill cycling.

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