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BIODYNAMICS

Physiological and biomechanical factors associated with elite endurance cycling performance

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ABSTRACT

COYLE, E. F., M. E. FELTNER, S. A. KAUTZ, M. T. HAMILTON, S. J. MONTAIN, A. M. BAYLOR, L. D. ABRAHAM, and G. W. PETREK. Physiological and biomechanical factors associated with elite endurance cycling performance. *Med. Sci. Sports Exerc.*, Vol. 23, No. 1, pp. 93–107, 1991. In this study we evaluated the physiological and biomechanical responses of "elite-national class" (i.e., group 1; $N = 9$) and "good-state class" (i.e., group 2; $N = 6$) cyclists while they simulated a 40 km time-trial in the laboratory by cycling on an ergometer for 1 h at their highest power output. Actual road racing 40 km time-trial performance was highly correlated with average absolute power during the 1 h laboratory performance test ($r = -0.88$; $P < 0.001$). In turn, 1 h power output was related to each cyclists' $\dot{V}O_2$ at the blood lactate threshold ($r = 0.93$; $P < 0.001$). Group 1 was not different from group 2 regarding $\dot{V}O_{2max}$ (approximately 70 $ml \cdot kg^{-1} \cdot min^{-1}$ and 5.01 $l \cdot min^{-1}$) or lean body weight. However, group 1 bicycled 40 km on the road 10% faster than group 2 ($P < 0.05$; 54 vs 60 min). Additionally, group 1 was able to generate 11% more power during the 1 h performance test than group 2 ($P < 0.05$), and they averaged 90 ± 1% $\dot{V}O_{2max}$ compared with 86 ± 2% $\dot{V}O_{2max}$ in group 2 ($P = 0.06$). The higher performance power output of group 1 was produced primarily by generating higher peak torques about the center of the crank by applying larger vertical forces to the crank arm during the cycling downstroke. Compared with group 2, group 1 also produced higher peak torques and vertical forces during the downstroke even when cycling at the same absolute work rate as group 2. Factors possibly contributing to the ability of group 1 to produce higher "downstroke power" are a greater percentage of Type I muscle fibers ($P < 0.05$) and a 23% greater ($P < 0.05$) muscle capillary density compared with group 2. We have also observed a strong relationship between years of endurance training and percent Type I muscle fibers ($r = 0.75$; $P < 0.001$). It appears that "elite-national class" cyclists have the ability to generate higher "downstroke power", possibly as a result of muscular adaptations stimulated by more years of endurance training.

ENDURANCE TRAINING, MUSCLE, FIBER TYPE, CAPILLARIZATION, BLOOD LACTATE THRESHOLD, MITOCHONDRIA, PEDALING MECHANICS, CYCLING POWER, HUMAN PERFORMANCE

We have recently reported that muscle glycogen use, lactate production, and endurance performance can vary greatly among competitive cyclists with an equally high maximum O_2 consumption (i.e., $\dot{V}O_{2max}$; 4.6–5.0 $l \cdot min^{-1}$) (8). Exercise time to fatigue at 88% of $\dot{V}O_{2max}$ was highly related ($r = 0.90$; $P < 0.001$) to the blood lactate threshold (LT), which reflected the degree of glycogen use and lactate production. The factors associated with a high $\%\dot{V}O_{2max}$ at LT were years of cycling experience ($r = 0.75$; $P < 0.01$) and percentage of Type I muscle fibers ($r = 0.55$; $P < 0.05$). Therefore, this first study suggested that intense cycle training performed for more than approximately 2 yr promotes continued muscular and/or neurological adaptations that reduce muscle glycogenolysis specifically when cycling. It became clear that, in addition to muscular adaptations, possible alterations in the biomechanics of cycling technique could contribute to improvements in LT and performance with continued years of training.

In the present investigation, we continued to investigate endurance cycling performance by taking three new approaches. First, using an instrumented pedal dynamometer, we determined a number of biomechanical parameters that characterized the pedaling techniques of "elite" compared with "good" competitive cyclists. Second, we evaluated physiological and bio-

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mechanical responses of "elite" cyclists (specializing in the 40 km time-trial) with the premise that they possess the optimal characteristics important to performance. Finally, in addition to obtaining the subjects' actual road time for a "40 km time-trial", the cyclists also simulated competitive conditions in the laboratory by cycling for 1 h at their highest power while their physiological and biomechanical responses were monitored. In this way it was possible to better describe the demands and factors which limit cycling performance of this duration.

METHODS

Subjects and training. Fifteen male competitive USCF category 1 or 2 cyclists were recruited for this study, in the spring of 1988, based upon their performance when bicycling a 40 km time-trial (i.e., bicycling alone) on a flat sea level course during the previous 12 months. This study was approved by the Institutional Review Board at the University of Texas, and the subjects provided written informed consent. The subjects whose recent best time for a 40 km time-trial was faster than 56 min were placed in group 1 ("elite-national class"), whereas subjects with slower performances were placed in group 2 ("good-state class"). The training and performance histories of these subjects are presented in Table 1. It should be noted that group 1 contained several of the United States' best "time-trial" cyclists.

General laboratory testing sequence. Testing was performed during two or three separate laboratory visits, over a 3–7 d period, during which the subjects' training and diet were standardized. All subjects consumed a high carbohydrate diet (>500 $g \cdot d^{-1}$) and limited their training on the day prior to testing.

On the 1st d, the study was explained, histories were recorded, and the following tests were performed. The subjects cycled on a stationary ergometer for 25 min, with work rate increasing every 5 min. Pedaling technique and blood lactate responses were determined during the 5th min of cycling at approximately 55, 65, 75, 85, and 95% of $\dot{V}O_{2max}$. After a 30 min rest, blood lactate was also measured when running for 20 min on a treadmill set at a 10% grade while speed was increased every 5 min. Following another 30–60 min rest, maximal oxygen consumption ($\dot{V}O_{2max}$) when cycling was determined.

On the 2nd d, the subject reported to the laboratory in the morning after a light breakfast. Body composition was determined by hydrostatic weighing. Cycling per-

TABLE 1. Characteristics of the subjects, including history of cycling performance.

Subject	Age (yr)	Years Cycling (yr)	Years Endurance (yr)	Cycle Train ($km \cdot wk^{-1}$)	40 km Time-Trial (min)	Recent Bicycle Racing Performance History
Group 1						
A	24	10	10	648	51.0	1st in 1987 National TT; 1st in 1987–88 National Team TT; 2nd in 1988 National TT
B	24	4	6	769	52.5	2nd in Pan Am trial; 13th in 1987 National TT; 1st in several road races
C	26	8	11	689	52.5	1st in 1985 National Team TT; 2nd in 1985 National TT; 1st in several road races
D	21	9	9	567	54.0	1st in 1987 Olympic Festival TT; 15th in 1987 National TT; 5th in 1987 Pan Am TT
E	32	2	11	243	54.0	1st in 1988 30–35 yr National TT; 3rd in 1988 Texas TT
F	19	4	4	567	54.0	14th in 1987 National TT; 1986 Junior World Team
G	21	7	9	688	55.5	2nd in 1987 Olympic Festival Team TT; 1st in several road races
H	21	4	7	421	55.5	1st in 1988 Collegiate Road Racing Nationals; 11th in 1988 Texas TT; 1st in several road races
I	26	3	12	259	56.0	1st in Canadian National Triathlon; Professional Triathlete
Mean	24	5.7	8.8*	539	53.9*	
±SE	4	1.0	0.9	63	0.5	
Group 2						
J	21	3	4	510	57.0	10th in 1987 Texas TT
K	21	2	5	486	59.0	8th in 1988 Collegiate National TT; 3rd in 1988 Texas Criterium
L	25	6	6	445	59.0	26th in 1988 Texas TT
M	22	7	7	607	61.0	14th in 1984 National Road Race; 2nd in 1988 Texas Pursuit Race
N	18	5	5	680	59.0	7th in 1988 Texas Road Race; 1st in 1987 Junior World Trials
O	25	2	3	446	65.0	Top 5 finish in local criterium races
Mean	23	4.2	5.0	529	60.0	
±SE	3	0.9	3	39	1.1	

Group 1 significantly different from group 2 using Student's *t*-test: * $P < 0.01$.

formance was then evaluated in the laboratory by the amount of work that an individual could perform in exactly 1 h while cycling a specially designed ergometer. Fifteen minutes following this performance test, a muscle biopsy of the vastus lateralis was performed to analyze muscle fiber type, enzyme activity, capillarization, and myoglobin.

Measurement of $\dot{V}O_{2max}$. A Monark ergometer (model 819) equipped with a racing seat and drop handlebars and pedals for cleated shoes was used for all cycle testing. The pedal's crank length was 170 mm. $\dot{V}O_{2max}$ was measured during continuous cycling lasting between 8 and 10 min, with work rate increasing every 2 min. A leveling off of $\dot{V}O_2$ generally occurred in all subjects. The subjects breathed through a Daniels valve; expired gases were continuously sampled from a mixing chamber and analyzed for O_2 (Applied Electrochemistry S3A) and CO_2 (Beckman LB-2). Inspired air volumes were measured using a dry gas meter (Parkinson-Cowan CD4). These instruments were interfaced with an Apple IIe computer, which calculated $\dot{V}O_2$ every 30 s.

Blood lactate threshold (LT). The subjects pedaled the Monark ergometer (model 819) continuously for 25 min, at work rates eliciting approximately 55, 65, 75, 85, and 95% of $\dot{V}O_{2max}$ for each successive 5 min stage. The ergometer was set in the constant power mode, and the subjects maintained a cadence of 90 rpm. Blood samples were obtained from a catheter in an antecubital vein during the 5th min of exercise at each stage. One milliliter of blood was deproteinized in 2 ml of perchloric acid and later analyzed for lactate (13). The blood lactate threshold was determined, as previously described (9), by graphing the lactate vs $\dot{V}O_2$ relationship and determining the $\dot{V}O_{2max}$ at which lactate increased 1 mM above baseline (i.e., the lactate at low intensity exercise). $\dot{V}O_2$ was averaged during the last 2 min of each 5 min stage. The subjects were fan-cooled during all exercise tests.

The blood lactate thresholds of the subjects were also determined while running for 20 min at four speeds on a treadmill set at a 10% grade, which elicited 60–90% of $\dot{V}O_{2max}$. This test was incorporated to provide an additional comparison of the groups during an activity other than cycling which stresses the quadriceps muscles. In our previous study (8), we found that the less experienced cyclist had higher blood lactate concentrations at a given $\dot{V}O_2$ when cycling compared with running.

Laboratory performance test. Performance was evaluated by determining the highest average work rate that each subject could maintain for 1 h, using the Monark ergometer (model 819). The subjects were allowed to vary both the resistance on the flywheel and pedal cadence, which were monitored continuously, in selecting the power output. After positioning the seat and handlebars, the subjects cycled intermittently for 1–2 min periods at the approximate performance work rate, as part of their warm-up. The initial work rate was set based upon a performance prediction from the results of the previous day's LT evaluation (8) as well as from the subject's perception during warm-up. The subjects were asked to maintain this initial work rate for 8 min, after which it could be adjusted up or down. During the test, the subjects had a visual display of the elapsed time, pedal cadence, flywheel resistance, work rate, and their heart rate. They were strongly encouraged by the investigators and two teammates. The average blood lactate concentration was determined from samples obtained via venipuncture at 30 and 60 min. $\dot{V}O_2$ was measured for 2 min of every 15 min period or when work rate was adjusted by more than 30 W.

Enzyme analysis, myoglobin, fiber typing, fiber area, and capillarization. The muscle samples for enzyme analysis were weighed and homogenized in buffer (pH 7.4) containing 50% glycerol, 20 mM sodium phosphate, 5 mM EDTA, and 0.02% bovine serum albumin. The activities of citrate synthase, β-hydroxyacyl-CoA dehydrogenase (β-OAC), phosphofructose kinase (PFK), and lactate dehydrogenase (LDH) were measured fluorometrically as described by Chi et al. (7). The enzymatic assays were conducted at 30°C and expressed relative to protein concentration (7). The myoglobin concentration of the muscle biopsy sample was determined by radioimmunoassay (22) with reagents from Nuclear Medical Systems.

The muscle samples prepared for histochemical analysis were sectioned transversely (10 μm) at −20°C using a Cryostat microtome. The distribution of Type I, Type IIa, and Type IIb fibers was determined from sections stained for adenosinetriphosphatase at pH 4.3 and 4.55 (4). Other sections were fixed, treated with a 1% amylase solution, and stained with periodic acid Schiff's reagent to visualize capillaries (1). These stained sections were analyzed by magnifying (×300) and projecting at least six artifact-free areas (0.25-mm²) within each section. The number of fibers and capillaries within the known area were determined, as was the average number of capillaries around the whole fibers.

Apparatus for measuring cycling technique. To obtain information of the pedaling technique of each cyclist, an instrumented pedal dynamometer was used (16,23). The pedal dynamometer was equipped with a potentiometer that produced an analog signal that was related to the pedal orientation and two analog signals that indicated the magnitude of the components of the force applied to the pedal that were oriented normal (F_N) and tangential (F_T) to its superior surface. The pedal dynamometer was mounted on the right side of a Monark model 819 ergometer, and it allowed each subject to use his normal racing shoes and cleats. The ergometer was equipped with a potentiometer that was attached to the crank and produced an analog signal that was directly related to the crank orientation (θ). The four analog signals described above were then converted to digital information, sampled at a rate of 550 Hz, and stored in the memory of an IBMC PC-AT microcomputer while each cyclist rode on the ergometer. The four signals were collected for ten consecutive pedal revolutions during the 4th min of each 5 min stage when each subject rode at 55, 65, 75, 85, and 95% of $\dot{V}O_{2max}$ during the LT determination on the 1st day of testing.

For each of the ten crank revolutions sampled at each work rate, the data from the crank potentiometer were used to compute the orientation of the crank (θ) relative to a vertical axis, and the data from both potentiometers were used to calculate the orientation of the pedal (β) relative to a horizontal axis (Fig. 1a). However, for each revolution there were separate regions where each potentiometer reset and they produced spurious values in these transition zones (16,23). To correct the data in the transition zone for the crank, previously reported procedures were used to compute an average angular velocity for the crank during each revolution (16,23).

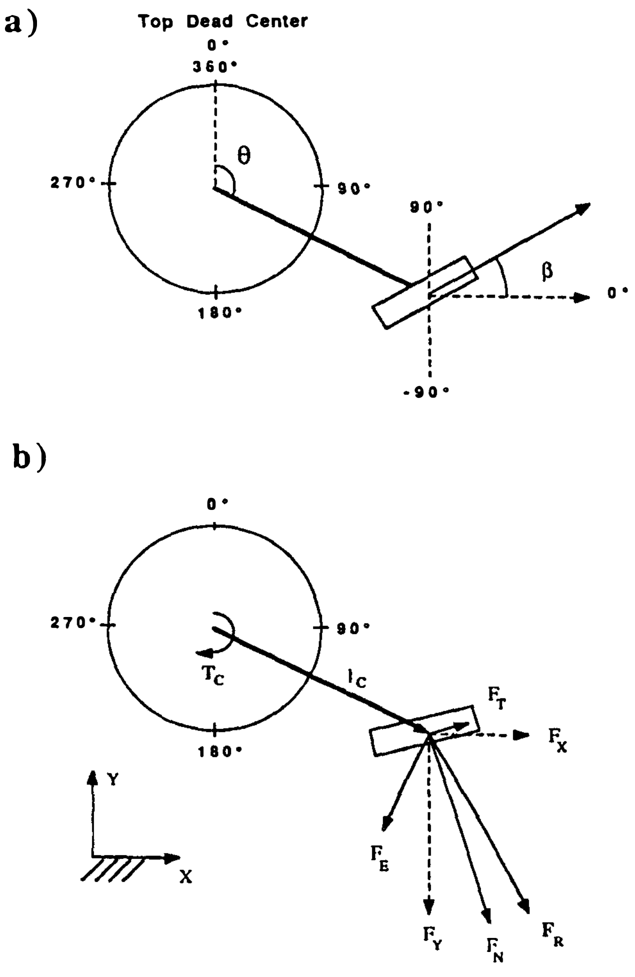

Figure 1—a) Reference values and signs for the crank (θ) and pedal (β) orientation. b) Sketch of the resultant force (F_R), horizontal force (F_X), vertical force (F_Y), tangential force (F_T), normal force (F_N), and effective force (F_E) applied to the pedal. Vector l_c represents the crank arm and T_C the torque created by F_R about the center of the crank. See text for details.

To compute the pedal orientation during the transition zone of the potentiometer attached to the pedal dynamometer, the values for the pedal orientation (β) from the portion of each revolution that was free from the effects of the transition zone were used to establish a least-squares fit for the function:

$$\beta = A\sin(t_{ri})^3 + B\cos(t_{ri})^3 + C\sin(t_{ri})^2 + D\cos(t_{ri})^2 + E\sin(t_{ri}) + F\cos(t_{ri}) + G,$$

where t_{ri} indicates the elapsed time from the beginning of each revolution and the terms A through G represent constants. All of the values for pedal orientation (β) during the revolution were then computed using the best fit curve. A similar curve ($\beta = A \sin t + B \cos t + C$) was used by Redfield and Hull (26), but the inclusion of the higher order terms provided a better fit for our data. The values of the force data (F_N and F_T) were filtered using a third-order recursive Butterworth low pass filter with a cutoff frequency of 30 Hz.

To better compare the data from each individual revolution and across subjects, the data describing the crank arm and pedal orientation (θ and β, respectively) and the normal and tangential components of the net force applied to the pedal (F_N and F_T, respectively) were linearly interpolated at instants that corresponded to discrete 1° increments from top dead center (TDC, θ = 0° or 360°), the start of each revolution, until the instant when the crank arm again passed through a position of 0° or 360°. Thus, at the completion of the data reduction, each of the values of β, F_N, and F_T were obtained for discrete 1 degree increments of θ from the start of each revolution. To better make comparisons among the subjects, the five consecutive crank revolutions where the angular velocity of the crank (w_c) was nearest to 90 rpm were averaged. This resulted in a data file for each subject that best represented the pedaling technique of the cyclist at each work rate.

Calculations. To aid in the interpretation of the force data, the values of β, F_N, and F_T were used to compute the horizontal (F_X) and vertical (F_Y) components of the net force applied to the pedal (F_R) at each instant during the revolution (Fig. 1b):

$$F_X = F_T\cos(\beta) - F_N\sin(\beta),$$

$$F_Y = F_T\sin(\beta) + F_N\cos(\beta).$$

The magnitude of F_R ($|F_R|$) was calculated using the Pythagorean theorem:

$$|F_R| = [(F_X)^2 + (F_Y)^2]^{1/2}$$

The net torque created about the center of the crank

(T_C) by F_R was computed by the following vector product:

$$T_C = l_c \times F_R,$$

where l_c is a vector pointing along the crank arm from the center of the crank to the center of the pedal (Fig. 1b).

The magnitude of the component of F_R that was perpendicular to the crank arm and that created a propulsive torque about the center of the crank at each instant of the crank revolution, the effective force ($|F_E|$), was computed as (Fig. 1b):

$$(|F_E| = (|F_R|^2 - [(l_c \cdot F_R)/|l_c|]^2)^{1/2},$$

where $l_c \cdot F_R$ is the scalar product of vectors l_c and F_R, and $(l_c \cdot F_R)/|l_c|$ is the magnitude of the component of F_R parallel to l_c. If T_C had a clockwise or propulsive value at each instant, the magnitude of F_E remained unchanged; however, if T_C had a counterclockwise or resistive value at an instant, then the magnitude of F_E was arbitrarily set to zero. In this manner, the effective force (F_E) indicated the component of F_R that contributed to a propulsive torque on the crank.

Two indices of effectiveness were computed to analyze the pedaling technique of the athletes. The first index (IE_{360}) was computed as the area under the F_E vs θ curve (Area $F_{E\text{-}360}$) divided by the area under the F_R vs θ curve (Area $F_{R\text{-}360}$) over the entire revolution:

$$IE_{360} = \frac{\int_0^{2\pi} F_E(\theta)\, d\theta}{\int_0^{2\pi} F_R(\theta)\, d\theta} \times 100.0.$$

The second index (IE_{180}) compared the effectiveness during the downstroke only (θ between 0° and 180°):

$$IE_{180} = \frac{\int_0^{\pi} F_E(\theta)\, d\theta}{\int_0^{\pi} F_R(\theta)\, d\theta} \times 100.0.$$

Two additional parameters were also defined. The work done by the cyclist during each revolution was computed as the area under the T_C vs θ curve.

$$W_{T_C} = \int_0^{2\pi} T_C(\theta)\, d\theta.$$

Single leg power (P_{SL}) values, defined by Davis and Hull (10), were also computed to compare the pedaling techniques of the two groups.

$$P_{SL} = \frac{1}{t_{rev}} \int_0^{2\pi} T_C(\theta)\, d\theta.$$

Finally, a third index expressed the ratio of the amount of positive work done during the downstroke to the amount of positive work produced over the entire revolution.

$$\%W_{180} = \frac{\int_0^{2\pi} T_C(\theta)\, d\theta}{\int_0^{2\pi} T_C(\theta)\, d\theta} \times 100.0.$$

We think it most appropriate to describe the pedaling technique of the subjects when cycling at 90 rpm at a work rate which is close to the average power maintained during the 1 h performance test. Therefore, for each subject, the work rate during the LT determination on day 1 which was within 10 W of the average power maintained by the cyclist during the 1 h laboratory performance test was analyzed for comparison. Additionally, to determine how the cyclists pedaled at an equivalent work rate, the data collected on day 1 for the cyclists were compared at the work rate that was within 5 W of 162 W for single leg power (P_{SL}) for each subject.

Statistics. Statistical comparisons between groups 1 and 2 were made for mean differences using Student's *t*-test for unpaired observations. The product moment formula was used to calculate correlation coefficients. Forward multiple regression was used to predict 40 km time-trial performance and laboratory performance from all the variables reported in Tables 1–5.

RESULTS

Subject characteristics and responses. Individual physiological data for all 15 cyclists are reported in the tables which describe their training histories (Table 1), physical characteristics (Table 2), responses when cy-

TABLE 2. Physical characteristics of the cyclists.

Subject	Body Weight (kg)	Lean Body Weight (kg)	Height (cm)	Circumference Upper thigh (cm)	Circumference Mid-thigh (cm)	Circumference Calf (cm)
Group 1						
A	79.8	73.1	187.0	56.0	56.0	38.2
B	71.3	67.0	181.5	52.7	49.7	34.7
C	74.8	62.2	184.5	56.6	52.8	37.7
D	80.7	71.2	183.0	58.8	57.8	39.4
E	70.2	60.9	174.0	56.8	54.9	37.8
F	77.1	71.7	185.0	57.5	53.9	35.0
G	62.4	55.5	174.8	52.7	51.1	35.9
H	66.4	62.2	174.0	53.5	53.0	35.5
I	73.2	66.6	177.5	57.9	48.0	36.1
Mean	72.8	65.6	180.1	55.8	53.0	36.7
±SE	2.0	1.9	1.7	0.8	1.0	0.5
Group 2						
J	73.9	67.5	178.5	54.8	53.0	35.1
K	81.2	74.2	183.8	57.3	54.3	37.8
L	69.0	64.8	173.3	53.0	51.7	38.7
M	75.7	67.6	180.8	55.7	53.0	36.5
N	62.1	60.2	173.0	51.5	50.9	34.9
O	62.0	57.9	168.5	51.4	50.0	34.5
Mean	70.7	65.4	176.3	53.9	52.1	36.2
±SE	3.1	2.4	2.3	1.0	0.6	0.7

cling at $\dot{V}O_{2max}$ and at LT (Table 3), responses during the 1 h laboratory performance test (Table 4), and muscle histochemistry, myoglobin, and enzyme activity (Table 5). These variables were used for the regression analysis described below.

Forty kilometer time-trial performance. Time-trial performance for 40 km among the 15 cyclists ranged from 51 min in the national champion to 65 min (Table 1). Time-trial performance was highly correlated ($r = -0.88$; $P < 0.001$) with the average absolute work rate maintained during the 1 h laboratory performance test (Fig. 2). It should be mentioned that exclusion of the slowest subject (i.e., subject 0) does not alter the correlation significantly ($r = -0.80$; $P < 0.001$). Time-trial performance was related to the average $\dot{V}O_2$ maintained during the 1 h laboratory performance test when expressed in absolute $l \cdot min^{-1}$ ($r = -0.834$; $P < 0.001$), whereas, when it is expressed relative to body weight (i.e., $ml \cdot kg^{-1} \cdot min^{-1}$), the correlation was not significant ($r = -0.39$; NS).

Using forward multiple regression, the five factors which best predicted time-trial performance were: 1) average absolute work rate for 1 h performance, $r^2 = 0.78$; 2) muscle capillary density (capillaries per mm^2), $r^2 = 0.94$; 3) muscle PFK activity, $r^2 = 0.97$; 4) lean body weight, $r^2 = 0.98$; and 5) $\dot{V}O_{2max}$ at LT ($l \cdot min^{-1}$), $r^2 = 0.99$.

TABLE 3. Responses when cycling at maximum oxygen consumption and at the blood lactate threshold.

	$\dot{V}O_{2max}$		$\dot{V}O_2$ at LT	
Subject	($l \cdot min^{-1}$)	($ml \cdot kg^{-1} \cdot min^{-1}$)	(%$\dot{V}O_{2max}$)	($l \cdot min^{-1}$)
Group 1				
A	5.65	70.8	79	4.40
B	5.27	73.9	79	4.14
C	5.26	70.3	84	4.40
D	5.19	64.4	76	3.94
E	5.14	73.2	75	3.71
F	5.05	65.6	81	4.08
G	4.56	73.0	77	3.50
H	4.66	70.1	84	3.93
I	4.82	65.5	78	3.77
Mean	5.07	69.6	79.2*	3.99†
±SE	0.11	1.2	1.1	0.10
Group 2				
J	5.36	72.5	74	3.95
K	5.31	65.4	80	4.23
L	4.80	69.6	80	3.84
M	5.11	67.8	71	3.60
N	4.51	72.6	74	3.34
O	4.20	67.7	73	3.08
Mean	4.88	69.3	75.3	3.67
±SE	0.19	1.2	1.5	0.17

$\dot{V}O_{2max}$, maximum oxygen consumption; LT, lactate threshold. Group 1 is significantly different from group 2 using Student's *t*-test: * $P < 0.05$; † $P = 0.11$.

TABLE 4. Responses during the 1 h laboratory performance test.

	Average $\dot{V}O_2$ during 1 h performance		Average Work Rate	Cycling Economy	Average Blood Lactate
Subject	($l \cdot min^{-1}$)	%$\dot{V}O_{2max}$	(W)	($W \cdot l^{-1} \cdot min^{-1}$)	(mM)
Group 1					
A	5.00	89	376	75.2	7.9
B	4.91	92	359	73.1	6.3
C	4.59	87	363	79.2	4.9
D	4.62	89	357	77.4	7.3
E	4.39	85	336	76.6	6.0
F	4.54	90	360	79.3	7.8
G	4.32	95	307	71.1	10.0
H	4.37	94	331	75.9	9.4
I	4.12	86	325	78.8	3.9
Mean	4.54*	89.7†	346*	76.3	7.1
±SE	0.09	1.1	7	1.0	0.7
Group 2					
J	4.67	87	335	71.8	9.0
K	4.54	86	336	73.9	4.5
L	4.26	89	326	76.6	6.9
M	4.00	78	313	78.4	6.8
N	3.94	87	300	76.1	8.0
O	3.69	88	256	69.2	8.9
Mean	4.18	85.8	311	74.3	7.4
±SE	0.15	1.6	12	1.4	0.7

Cycling Economy is defined as the average work rate divided by average $\dot{V}O_2$ during the 1 h performance test. Group 1 is significantly different from group 2 using Student's *t*-test: * $P < 0.05$; † $P = 0.06$.

Laboratory performance. The average work rate maintained during the 1 h laboratory performance test was best correlated to $\dot{V}O_2$ at LT ($r = 0.93$; $P < 0.001$; Fig. 3). Using forward multiple regression, the five factors which best predicted 1 h laboratory performance were: 1) $\dot{V}O_2$ at LT ($l \cdot min^{-1}$), $r^2 = 0.86$; 2) percent Type I muscle fibers, $r^2 = 0.91$; 3) calf circumference, $r^2 = 0.92$; 4) mid-thigh circumference, $r^2 = 0.95$; and 5) muscle myoglobin concentration, $r^2 = 0.97$.

Comparison of time-trial and laboratory performance differences between groups I and 2. Groups 1 and 2 were compared with the aim of gaining insight regarding the factors related to their differences in performance. Forty kilometer time-trial performance was 10% faster in group 1 than in group 2 (53.9 ± 0.5 vs 60.0 ± 1.1 min, respectively; $P < 0.01$; Table 1). During the 1 h laboratory performance test, group 1 maintained an 11% higher power output than group 2 (346 ± 7 vs 311 ± 12 W; $P < 0.05$; Table 4). Group 1 also maintained an average $\dot{V}O_2$ ($l \cdot min^{-1}$) while performing that was 9% higher than that of group 2 (4.54 ± 0.09 vs 4.18 ± 0.15 $l \cdot min^{-1}$; $P < 0.05$; Table 4). Additionally, group 1 was able to maintain a higher %$\dot{V}O_{2max}$ during the 1h performance test (89.7 ± 1.1 vs 85.8 ± 1.6% of $\dot{V}O_{2max}$; $P < 0.06$; Table 4).

Pattern of torque production. Figure 4 a and b present the plots of crank torque (T_C) vs crank orientation (θ) for the individual subjects in group 1 and group 2, respectively. The average pattern of torque production for group 1 vs group 2 is shown in Figure 5. The plots of the average pedal angle (β) vs θ for the two groups are presented in Figure 6a, and the curves of the average vertical (F_Y) and horizontal (F_X) forces applied to the pedal by the cyclists are presented in Figure 6 b and c, respectively. Individual data that serve

TABLE 5. Muscle histochemistry, myoglobin, and enzyme activity.

Subject	Fiber Type (%) I	IIa	IIb	Fiber Area (μm^2)	Capillarization: capillaries per fiber	capillaries per mm²	Myoglobin ($g \cdot kg^{-1} \cdot p$)	Cit. Syn. ($mol \cdot kg^{-1}\, p \cdot h^{-1}$)	βOAC ($mol \cdot kg^{-1}\, p \cdot h^{-1}$)	PFK ($mol \cdot kg^{-1}\, p \cdot h^{-1}$)	LDH ($mol \cdot kg^{-1}\, p \cdot h^{-1}$)
Group 1											
A	62.0	38.0	0.0	8522	3.64	427	39.6	11.0	11.9	30.8	28.8
B	52.6	47.4	0.0	7234	3.13	433	50.3	14.4	13.2	33.8	21.5
C	75.7	24.4	0.0	7571	3.03	400	39.3	13.2	15.5	28.5	17.2
D	83.2	16.8	0.0	6956	2.99	430	32.1	8.7	14.6	21.5	15.0
E	76.5	23.5	0.0	4994	2.29	459	31.5	10.6	12.2	24.1	12.7
F	56.4	43.6	0.0	7326	2.66	363	27.6	10.2	12.5	25.9	20.0
G	59.3	34.0	6.7	5500	3.37	613	22.8	8.7	13.6	31.4	27.5
H	57.1	42.9	0.0	6015	2.60	518	22.6	8.0	7.7	19.6	22.2
I	75.6	24.4	0.0	4537	2.40	529	35.8	15.5	11.6	26.3	16.5
Mean	66.5*	32.8	0.7	6406	2.90	464*	33.5†	11.2§	12.5§	26.9	20.2†
±SE	3.7	3.6	0.7	470	0.15	25	8.9	0.9	0.7	1.6	1.8
Group 2											
J	46.3	48.5	1.5	6906	2.78	403	25.4	7.6	9.52	19.6	26.9
K	48.9	40.9	10.0	8343	2.73	327	25.0	9.0	10.1	24.6	31.9
L	65.4	34.6	0.0	9382	3.19	340	27.5	11.6	15.9	25.0	14.9
M	63.6	35.9	0.5	5429	2.06	379	21.1	6.5	6.3	17.2	40.7
N	63.7	28.6	7.7	5814	2.75	473	31.7	13.0	11.5	19.5	26.4
O	29.6	60.3	10.1	6752	2.31	342	25.4	7.1	10.7	41.4	24.0
Mean	52.9	41.5	5.1	7104	2.64	377	26.0	9.3	10.7	24.5	27.5
±SE	5.7	4.6	1.9	615	0.16	22	1.4	1.1	1.3	8.8	3.5

Myoglobin concentration and enzyme activities are expressed relative to muscle protein concentration ($g \cdot kg^{-1}$ p). Activities of the enzymes citrate synthase (Cit. Syn.), β-hydroxyacyl-CoA dehydrogenase (βOAC), phosphofructokinase (PFK), and lactate dehydrogenase (LDH) were determined at 30°C. Group 1 is significantly different from group 2 using Student's *t*-test: * $P \leq 0.05$; † $P = 0.07$; § $P \leq 0.18$.

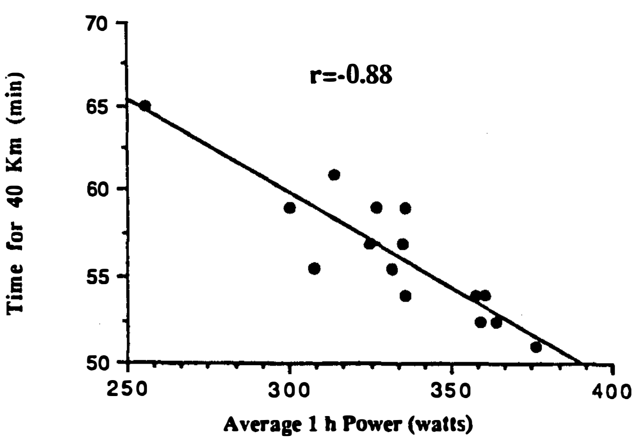

Figure 2—Relationship between the average power maintained during the 1 h laboratory performance test and the cyclists' road racing time for 40 km. r = −0.88; *P* < 0.001. y = 92.4 − 0.10839x.

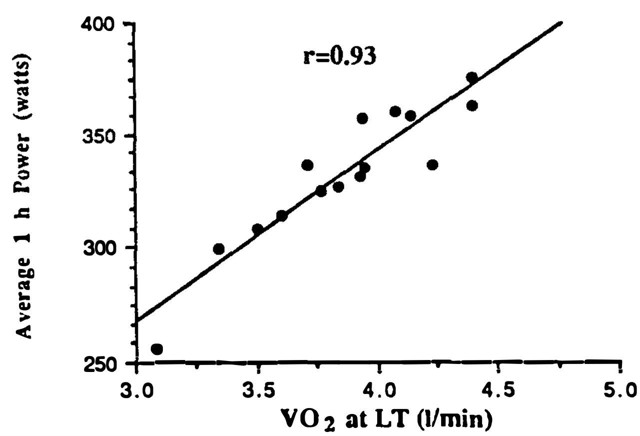

Figure 3—Relationship between the oxygen consumption at the blood lactate threshold ($\dot{V}O_2$ at LT) and the average power maintained during the 1 h laboratory performance test. r = 0.93; *P* < 0.001. y = 75.32x + 41.37.

to quantify the pedaling technique at the performance work rate of each cyclist are presented in Table 6.

The data demonstrated that the cyclists in group 1 maintained an 11% higher ($P < 0.05$) power output (Table 4) by doing 9% more work (W_{Tc} in Table 6; $P < 0.2$) over the entire pedal stroke. The increased amount of work performed by the cyclists in group 1 was due to the larger propulsive torques created by the cyclists during the downstroke portion of the pedal stroke ($\theta = 0°–180°$) (Figs. 4 and 5). The large propulsive torque values are also reflected in the significantly larger peak torque values produced by the cyclists of group 1 during the downstroke (76.8 ± 7.6 vs 62.8 ± 13.8 N·m; $P < 0.05$; Table 6). Interestingly, the subjects of group 1 produced the larger propulsive torques by creating significantly ($P < 0.05$) larger forces in the vertical direction on the pedal during the downstroke (peak F_Y in Table 6 and Fig. 6b) and by not attempting to pull up on the pedal during the upstroke (near zero values for F_Y in Fig. 6b between $\theta = 240°$ and $\theta = 340°$). The pattern of horizontal force application to the pedal was more similar in the two groups (Fig. 6c).

These data indicated that the "elite" cyclists in group 1 adopted a pedaling strategy of applying large vertical forces to the pedal during the downstroke in an attempt

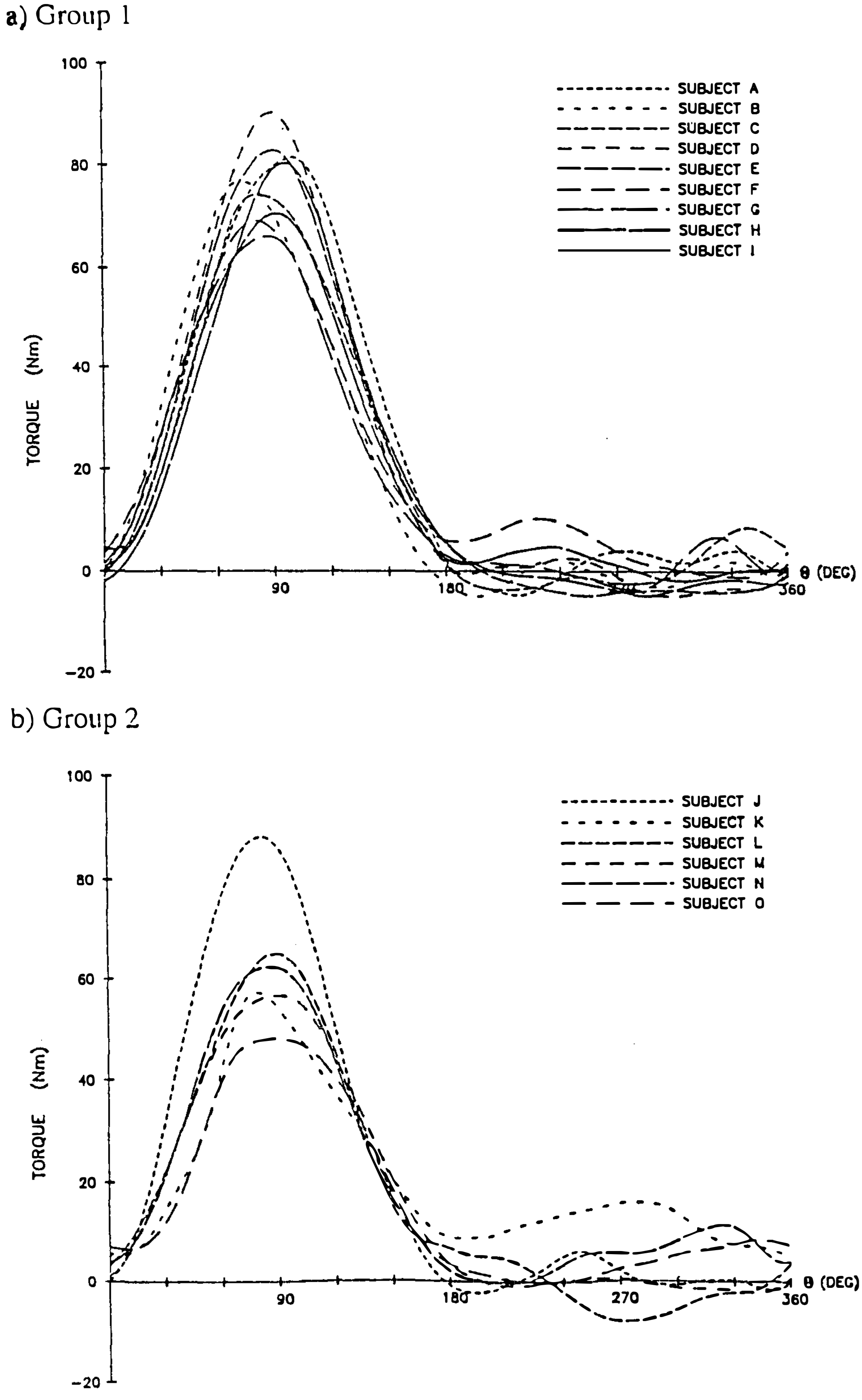

Figure 4—a) Plots of torque produced about the cranks (T_C) vs the crank orientation (θ) for the individual subjects of group 1. Zero degrees for (θ) is top dead center, and 180 degrees is bottom dead center. b) Plots of torque produced about the cranks (T_C) vs the crank orientation (θ) for the individual subjects of group 2. The work rate for each subject is listed in Table 4.

to maximize the amount of propulsive torque produced during this interval. Figure 5 indicates that group 2 used a similar strategy of generating propulsive torque during the downstroke, with two small differences. Group 2 applied smaller forces during the downstroke and sufficient upward force during recovery to generate small propulsive torques. As a result of this strategy, the magnitude of the propulsive torque produced dur-

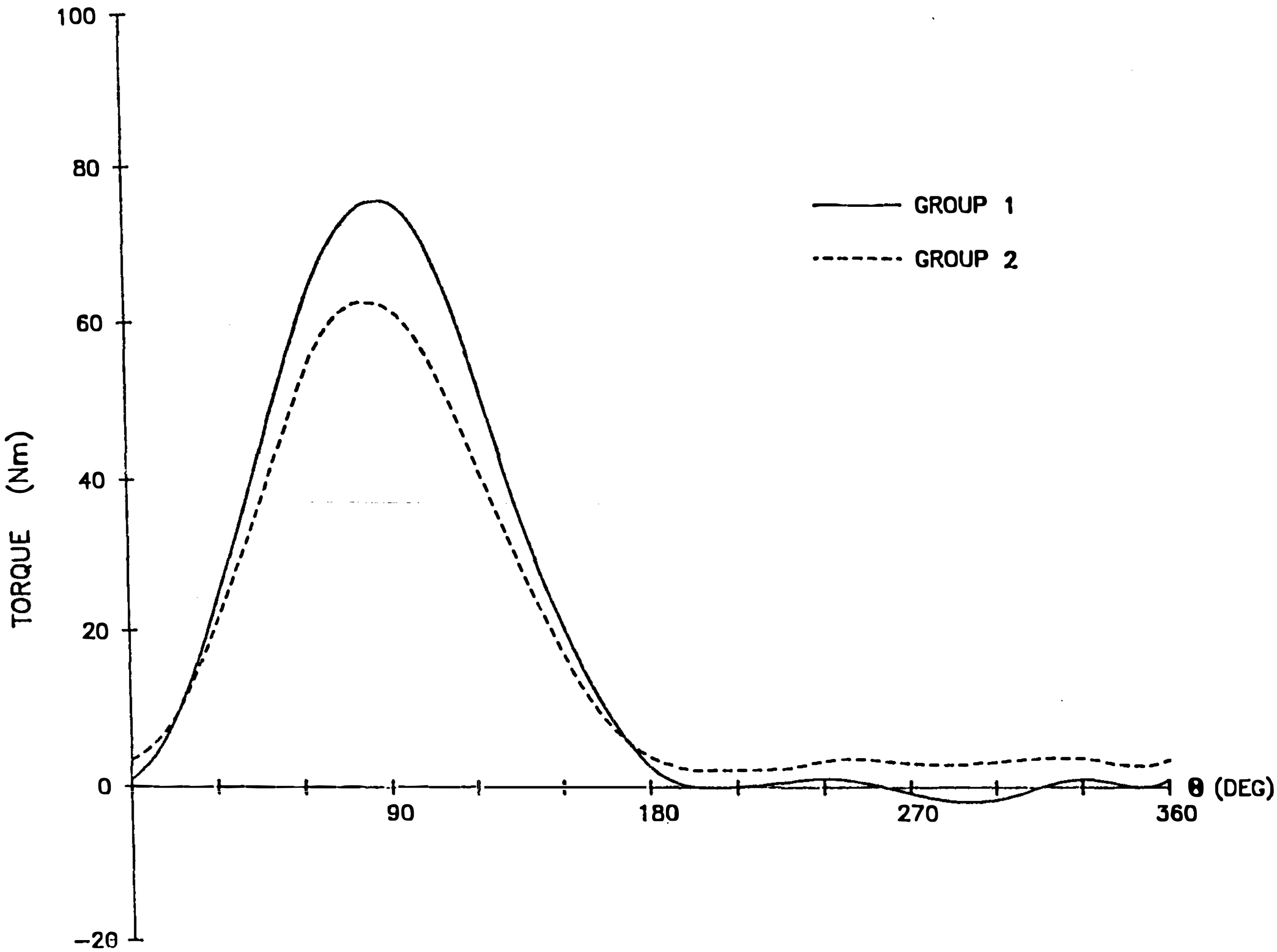

Figure 5—Comparison of the average torque production (T_C) vs crank orientation (θ) in group 1 and group 2 when cycling at the average power output maintained for 1 h.

ing the downstroke by the cyclists of group 2 and the total work performed by T_C during each revolution (W_{Tc}) were decreased. The consequences of these two strategies are reflected in the 7% larger ($P = 0.10$) value for $\%W_{180}$ for the cyclists of group 1. However, the large values of $\%W_{180}$ for both groups emphasize the importance of the downstroke for creating the propulsive torque and the relative unimportance, especially in the "elite-national class" cyclists, of the upstroke for creating propulsive torque (see Figs. 4 and 5 and Table 6).

The indices of effectiveness indicated that the subjects of group 2 were more effective in applying a force to the pedal and in creating a propulsive torque throughout the pedal revolution (see IE_{360} and IE_{180} in Table 6). The index of effectiveness of each group increased when only the downstroke was examined (see IE_{180} in Table 6). Thus, the values for the indices of effectiveness were enhanced by the pedaling strategy used by the cyclists of group 2 even though their pedaling strategy produced a smaller amount of work per revolution than the strategy employed by the cyclists of group 1.

Interestingly, the general pedaling technique of the cyclists in each group remained the same when the subject were all compared at the same power output (162 W for S_{LP}) and at a cadence of 90 rpm (Fig. 7 and Table 7). The subjects of group 1 continued to produce a higher peak propulsive torque during the downstroke (Fig. 7 and Table 7) by creating larger vertical forces during this interval (Table 7).

Physical comparison and training histories of groups 1 and 2. Although body size is important to time-trial performance, it did not account for the presently observed differences between groups 1 and 2 since lean body weight was identical (i.e., 65 kg; Table 2). Group 1 tended to be somewhat taller (2.1%; $P = 0.20$) and have a slightly larger upper-thigh circumference (3.5%; $P = 0.15$); yet these differences were relatively small.

Group 1 had been performing endurance exercise

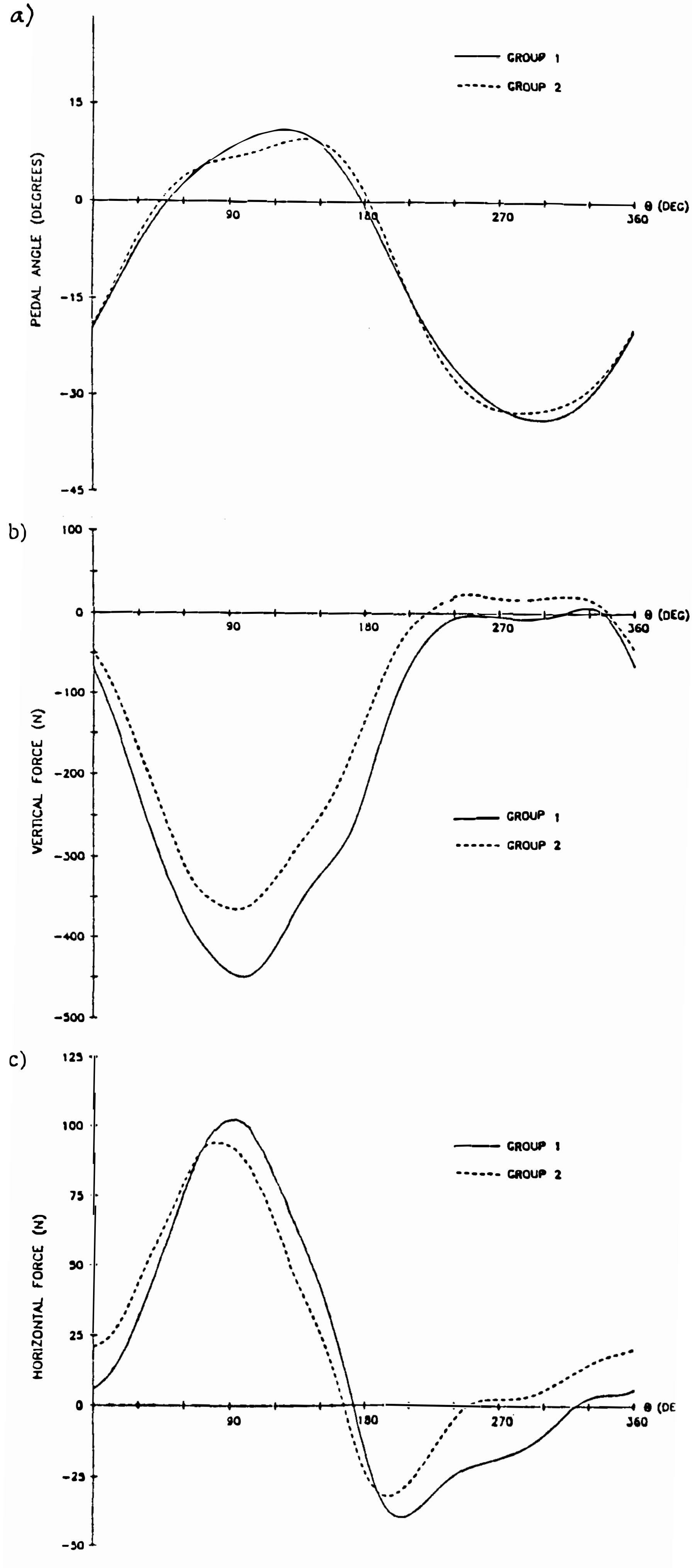

Figure 6. Display of a) average pedal angle (β) vs θ, b) average vertical force (F_V) vs θ, and c) average horizontal force (F_H) vs θ in group 1 and group 2 when cycling at the average power output maintained for 1 h.

TABLE 6. Biomechanical parameters of the pedaling technique for the cyclists at the right pedal when cycling at the average power output maintained during the 1 h performance bout.

Subject	W_{Tc} (J)	Peak T_C (N·m)	Peak F_Y (N)	IE_{180} (%)	IE_{360} (%)	% W_{180} (%)	θ at Peak T_C (°)	θ at Peak F_Y (°)
Group 1								
A	141	81	−515	67.2	58.3	96.4	98	112
B	118	77	−422	66.4	58.2	98.8	73	74
C	122	74	−435	71.3	63.8	95.5	81	100
D	137	90	−532	70.4	62.2	99.0	89	94
E	125	83	−495	75.6	65.0	99.5	89	98
F	129	69	−395	74.7	72.9	89.8	80	84
G	113	66	−389	68.9	61.8	95.7	86	94
H	118	80	−491	71.5	61.3	99.3	96	104
I	118	70	−426	71.3	68.2	95.9	90	102
Mean	124.5‡	76.8*	−455.6*	70.8†	63.5†	96.6†	86.9	95.8
±SE	3.1	0.8	17.8	1.0	4.7	1.0	0.9	3.7
Group 2								
J	139	88	−506	67.7	62.2	97.3	81	88
K	127	57	−320	82.8	80.7	72.1	79	84
L	101	65	−385	77.5	68.3	96.4	88	97
M	100	57	−342	70.4	59.4	99.4	90	103
N	120	62	−369	72.7	70.4	86.9	85	98
O	96	48	−295	77.8	74.8	88.5	90	115
Mean	113.8	62.8	−369.4	74.8	69.3	90.1	85.5	97.5
±SE	7.1	2.3	30.4	2.3	3.2	4.1	0.8	4.5

Values are means ± SE. W_{Tc}, work produced per revolution. Peak T_C, peak torque about the cranks. Peak F_Y, peak vertical force. IE_{180}, index of effectiveness between 0 and 180°. IE_{360}, index of effectiveness between 180 and 360°. %W_{180}, percentage of total work done during 0–180°. θ at Peak T_C, crank orientation at peak torque. θ at Peak F_Y, crank orientation at peak vertical force. Significant difference between group 1 and group 2: * $P < 0.05$; † $P < 0.10$; ‡ $P < 0.2$.

training for 8.8 ± 0.9 yr, whereas group 2 had been training for endurance for 5.0 ± 3.0 yr ($P < 0.01$; Table 1). However, their years of cycle training (i.e., 5.7 vs 4.2 yr) were not significantly different. The number of kilometers ridden in training during the 2 months prior to this study was similar in the two groups (Table 1).

$\dot{V}O_{2max}$ and LT of groups 1 and 2. $\dot{V}O_{2max}$ was not different in groups 1 and 2, who displayed identical mean values of approximately 70 ± 1 ml·kg^{-1}·min^{-1} (Table 3). When expressed in liters per minute, $\dot{V}O_{2max}$ was still not significantly different in groups 1 and 2 (5.07 ± 0.11 vs 4.88 ± 0.19 l·min^{-1}). However, the LT occurred at 79.2 ± 1.1% $\dot{V}O_{2max}$ in group 1 compared with 75.3 ± 1.5% $\dot{V}O_{2max}$ in group 2 ($P < 0.05$; Table 3). More importantly, the absolute $\dot{V}O_2$ at LT (l·min^{-1}) was 9% higher in group 1 than in group 2 (3.99 ± 0.10 vs 3.67 ± 0.17 (l·min^{-1}; $P = 0.11$).

Muscle characteristics of groups 1 and 2. Group 1 possessed a higher percentage of Type I fibers than did group 2 (66.5 ± 3.7 vs 52.9 ± 5.7% Type I; P = 0.05; Table 5). Additionally, only one of nine subjects in group 1 possessed any Type IIb fibers, whereas five out of six subjects in group 2 displayed Type IIb fibers. Group 1 also possessed a 23% higher muscle capillary density (464 ± 25 vs 377 ± 22 capillaries per mm^2; $P < 0.05$; Table 5) compared with group 2. Additionally, group 1 displayed a 29% higher myoglobin concentration (P = 0.07) and a 26% lower LDH activity (P = 0.07) than group 2. Citrate synthase and β-hydroxyacyl-CoA dehydrogenase activities were 20% and 17% higher in group 1 compared with group 2; yet the statistical significance was only P = 0.18 (Table 5).

Therefore, the vastus lateralis of the subjects in group 1 possessed a higher percentage of Type I fibers and greater muscle capillary density. They also appeared somewhat better trained based upon the observation that LDH activity was lower and citrate synthase activity tended to be higher.

DISCUSSION

One practical purpose of this study was to identify some factors associated with time-trial cycling performance. We observed that 40 km time-trial performance was most closely related (r = −0.88; $P < 0.01$) to the average absolute power output (i.e., watts) during the 1 h laboratory performance test (Fig. 2) and not power relative to body weight. This agrees with the idea that the power required to cycle at racing velocities (i.e., 37–47 km·h^{-1}) is not proportional to body weight (20,29). The close association between performance during the actual 40 km time-trial and the 1 h laboratory test indicates that the laboratory test simulated a time-trial reasonably well and that therefore these laboratory data generally describe the demands of this cycling event. We have observed "elite-national class" cyclists (group 1) to be capable of cycling at 90 ± 1% $\dot{V}O_{2max}$ and 346 ± 7 W for 1 h with an average blood lactate concentration of more than 7 mM (Table 4). The national champion at the time of this study averaged 376 W with a $\dot{V}O_2$ of 5 l·min^{-1} during the 1 h test. The cyclists of both group 1 ("elite-national class" cyclists) and group 2 ("good-state class") possessed equally high values for $\dot{V}O_{2max}$ (i.e., 70 ml·kg^{-1}·min^{-1} and approximately 5 l·min^{-1}). These values are comparable to previous reports on "elite-national class" cyclists (5,6,14). As with our previous study (8), we presently have observed that the factors which distinguish group 1 from group 2 are their %$\dot{V}O_2$ at LT (79.2 vs 75.3%; $P < 0.05$; Table 3) and a 9% higher absolute $\dot{V}O_2$ at LT (l·min^{-1}) (P = 0.11; Table 3). In this study, the average power output during the 1 h laboratory performance test was highly related to $\dot{V}O_2$ at LT (r = 0.93; $P < 0.001$; Fig. 2), which is similar to our previous observation that time to fatigue when cycling at 88% $\dot{V}O_{2max}$ was related to %$\dot{V}O_{2max}$ at LT. Therefore, LT in both the previous (8) and the present studies accurately predicted performance. However, the groups in the present study were more homogeneous than the groups in the previous study, whose %$\dot{V}O_{2max}$ at LT were 65.8 vs 81.5%, respectively. This indicates that

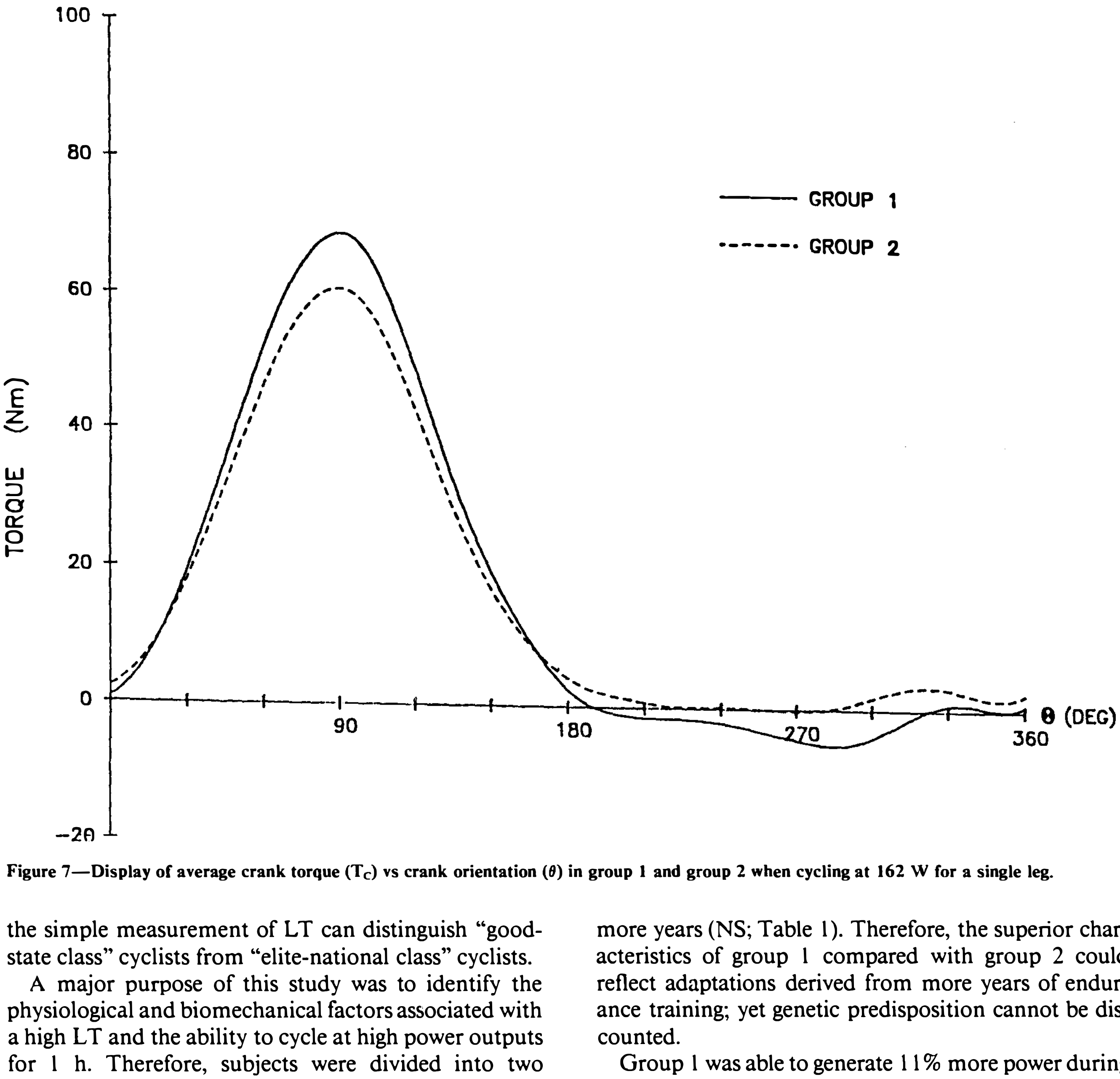

Figure 7—Display of average crank torque (T_C) vs crank orientation (θ) in group 1 and group 2 when cycling at 162 W for a single leg.

the simple measurement of LT can distinguish "good-state class" cyclists from "elite-national class" cyclists.

A major purpose of this study was to identify the physiological and biomechanical factors associated with a high LT and the ability to cycle at high power outputs for 1 h. Therefore, subjects were divided into two groups, based upon performance. This type of grouping and comparison is common because data can be more easily interpreted (5,6,25). However, it should be realized that, since the various characteristics span a continuum in this homogeneous population, it is sometimes more difficult to achieve group differences which are statistically significant (i.e., $P < 0.05$). Groups 1 and 2 were almost identical in lean body weight, and, therefore, more muscle mass did not appear responsible for the superior performance of group 1 (Table 2). It should be mentioned, however, that lean body weight was related to absolute 1 h power output (i.e., $r = 0.65$; $P < 0.01$) in the entire population. Group 1 had been performing endurance training for about four more years than group 2 (i.e., 8.8 ± 0.9 yr vs 5.0 ± 3.0 yr; $P < 0.05$); however, they had been cycling for only 1.5 more years (NS; Table 1). Therefore, the superior characteristics of group 1 compared with group 2 could reflect adaptations derived from more years of endurance training; yet genetic predisposition cannot be discounted.

Group 1 was able to generate 11% more power during the 1 h performance test than group 2 ($P < 0.05$; Table 4), and they maintained a 10% higher bicycling velocity for 40 km ($P < 0.05$; Table 1). It is clear from Figure 6 and Table 6 that the subjects of group 1 generated more power by producing peak vertical forces and crank torque that were larger in magnitude during the downstroke ($\theta = 0°–180°$) when compared with group 2. As a result, the cyclists of group 1 were able to do more work per revolution (W_{Tc} in Table 6), and, due to the similarities in their pedaling cadence, the subjects of group 1 could maintain a larger power output. However, the strategy employed by the "elite-national class" cyclists was less effective (in the sense of lower indices of effectiveness) than that used by the "good-state class" athletes as a larger proportion of the resultant force applied to the pedal did not create propulsive torque in

TABLE 7. Biomechanical characteristics of the pedaling technique at the right pedal when cycling at 162 W.

Subject	Peak T_C (N·m)	θ at Peak T_C (°)	Peak F_Y (N)	θ at Peak F_Y (°)
Group 1				
A	78	97	−482	106
B	68	78	−384	83
C	68	84	−407	104
D	74	89	−439	96
E	79	89	−470	97
F	51	83	−296	90
G	62	88	−366	96
H	74	96	−462	105
I	74	92	−447	101
Mean	69.7*	88.4	−416.9†	97.6
±SE	3.0	2.0	20.0	2.5
Group 2				
J	72	81	−413	88
K	50	88	−292	92
L	65	88	−385	97
M	60	97	−378	114
N	59	93	−359	102
O	63	98	−389	106
Mean	61.4	90.8	−369.1	99.8
±SE	3.1	2.6	17.1	3.9

Values are means ± SE. Peak T_C, peak torque about the cranks. θ at Peak T_C, crank orientation at peak torque. Peak F_Y, peak vertical force. θ at Peak F_Y, crank orientation at peak vertical force. Significant difference between group 1 and group 2; * $P < 0.10$; † $P < 0.15$.

the elite cyclists. Therefore, increased indices of pedaling effectiveness determined from the applied pedal forces do not correlate positively with performance. When the complex movement of cycling is considered in its biomechanical entirety (kinematics, dynamics, and muscular coordination), it is not surprising that a measure of effectiveness based solely on the orientation of the applied force fails to yield a meaningful measure of the true "effectiveness" of the movement. It is clear that any future research attempting to quantify effectiveness must consider more than the orientation of the applied pedal forces. This finding makes it unclear whether feedback devices that allow a cyclist to improve pedaling effectiveness (2,3,21) will lead to improved performance.

Differences between the power output and pedaling cadence utilized in the present investigation and those used in previous studies (10,11,16,18,19,21,27) made it difficult to compare the present data with previous biomechanical data. This is especially so since none of the previous studies characterized competitive cyclists under conditions similar to those of the 1 h performance ride. A consistent conclusion of the previous studies was that cyclists did not pull up on the pedal during the upstroke. However, the present study found less negative torque during the upstroke than the previous studies. In some instances this reduction in negative torque was produced by pulling up on the pedal. Data from our laboratory (Kautz et al., submitted for publication) indicate that the torque production patterns exhibited by a cyclist were similar with increasing work rates, with the major difference at higher power outputs being increased peak torque during the downstroke and, to a much lesser extent, reduced negative torque during the upstroke.

The next question concerns factors responsible for the ability of group1 to produce a larger peak torque through the application of a larger vertical force on the crank arm during the downstroke. Since pedaling effectiveness ($\bar{I}E_{360}$; Table 6) was lower in group 1, it appears that group 1 possessed the ability to recruit a relatively larger quantity of muscle with each revolution. Factors possibly contributing to this ability are the higher percentage of Type I fibers (66% vs 53%; $P < 0.05$) and the 23% higher ($P < 0.05$) muscle capillary density in group 1 compared with group 2 (Table 4). Additionally, group 1 displayed tendencies for higher citrate synthase activity ($P = 0.17$) and lower LDH activity ($P = 0.07$; Table 4). This profile of group 1 is similar to other reports of "extremely" well trained endurance athletes (17). It is likely that the muscle fiber type and enzyme characteristics of group 1 contributed to their high LT and remarkable ability to cycle for 1 h at 90% $\dot{V}O_{2max}$ (15). Additionally, high muscle capillary density may improve tolerance for this high intensity exercise by augmenting by-product removal from muscle (8,31).

It is possible that the higher power production during the downstroke displayed by group 1 compared with group 2 resulted, to some extent, from a different pattern of muscular utilization in the lower extremities during each revolution. The results seen here could indicate differences in the timing and activation patterns of the lower extremity musculature and/or differences in the intensity of the contractions of these same leg muscles. At present, we are attempting to address this question by examining the joint torques at the hip, knee, and ankle. Therefore, the exact factors that allowed the subjects of group 1 to generate more power and to produce higher peak torques during the cycling downstroke are unclear. It seems that part of the difference in the performance ability of the two groups resulted from metabolic muscular adaptations mentioned previously; however, it should be recognized that biomechanical factors which alter the distribution of work also have potential to reduce fatiguability and improve performance.

Even when cycling at a given power output (i.e., 162 W at the right pedal), group 1, who possessed a higher percentage of Type I muscle fibers, generated a higher peak torque during the downstroke compared with group 2 (Table 7 and Fig. 7). This observation is contrary to Suzuki (28), in that they observed experienced cyclists with a high percentage of Type I fibers to display lower peak torque production and more uniform pedal force application compared with noncyclists possessing a low percentage of Type II fibers. It is likely that the differences observed by Suzuki (28) reflect cycling skill and experience rather than the influence of muscle fiber type. This is because the subjects with a high percentage of Type I muscle fibers were experienced cyclists whereas the others were inexperienced.

In our previous study (8), the group of subjects who reached LT at 66% $\dot{V}O_{2max}$ (i.e., group L) appeared to be different from the group of subjects who reached LT at 82% of $\dot{V}O_{2max}$ (i.e., group H) in factors other than muscle mitochondrial activity. We speculated that these "low LT cyclists" may not yet have developed proper cycling technique, based upon the observation that their blood lactate threshold was markedly lower when cycling than when running uphill on a treadmill (8). Unlike the "low LT cyclists" in our previous study (8), all the subjects in the present study displayed a similar blood lactate response while running and cycling, and, therefore, we think they were all reasonably skilled cyclists. Groups 1 and 2 had been cycling for 5.7 yr and 4.2 yr, respectively, whereas the "low LT cyclists" in our previous study had been cycling for only 2.7 yr.

The percentage of Type I muscle fibers in the vastus lateralis of the subjects in this study was highly related (r = 0.80; $P < 0.001$) to the number of years spent performing endurance training with the legs. When combining the 15 subjects of this study with the 14 subjects in our previous study, the correlation between percent Type I and years of endurance training with the legs is r = 0.75 ($P = 0.001$; Fig. 8). Due to the cross-sectional design of this study, it is not possible to determine whether percent Type I actually increased in these cyclists as training duration progressed or whether those cyclists with the highest percent Type I continued to train and race for more years. However, it has been demonstrated that chronic electrical stimulation or extreme endurance training in animals can induce alterations in the metabolic and contractile properties of skeletal muscle which appear to reflect a transformation of Type II into Type I fibers (12,24). Additionally, Tesch and Karlsson (30) have observed that endurance athletes have a high percentage of Type I fibers in their trained muscles yet a normal percentage of Type I fibers in their untrained muscles.

In summary, we have observed in competitive cyclists that 40 km time-trial performance is closely related to absolute power during a 1 h laboratory performance test (r = −0.88; $P < 0.001$). In turn, 1 h power output

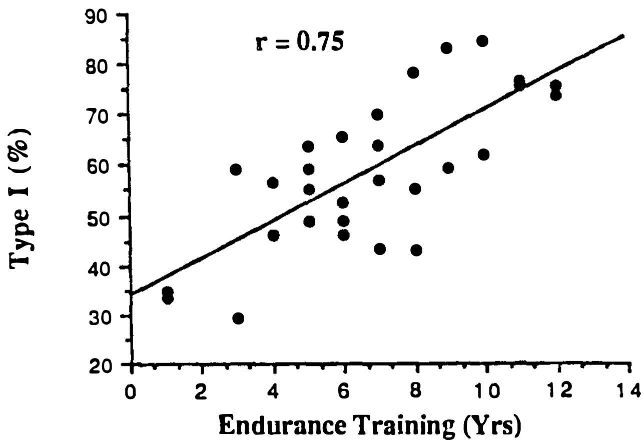

Figure 8—Relationship between the years of endurance training and % Type I muscle fibers. r = 0.75; $P < 0.001$. Subjects 10 and 13 of Coyle et al. (8) had been performing leg endurance training for 1–2 yr, although they had been swimming for many years.

is highly related to the cyclist's $\dot{V}O_2$ at LT (r = 0.93; $P < 0.001$). Although the "elite-national class" cyclists (group 1) were not different from the "good-state class" cyclists (group 2) regarding $\dot{V}O_{2max}$ or lean body weight, group 1 was able to generate 11% more power during the 1 h performance test than group 2 ($P < 0.05$), and they maintained a 10% higher bicycling velocity for 40 km ($P < 0.05$). The higher power output was produced primarily by generating higher peak vertical forces and torque during the cycling downstroke and not by increasing the effectiveness of force application to the pedal. Factors possibly contributing to this ability may be the higher percentage of Type I fibers ($P < 0.05$) and a 23% higher ($P < 0.05$) muscle capillary density in group 1 compared with group 2. Additionally, we have also observed a strong relationship between years of endurance training and percent Type I muscle fibers (r = 0.75; $P < 0.001$). It appears that "elite-national class" cyclists have the ability to generate higher "downstroke power", possibly as a result of adaptations stimulated by their greater number of years of endurance training.

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