Influence of Testing Protocol on Ventilatory Thresholds and Cycling Performance

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ABSTRACT

AMANN, M., A. SUBUDHI, and C. FOSTER. Influence of Testing Protocol on Ventilatory Thresholds and Cycling Performance. *Med. Sci. Sports Exerc.*, Vol. 36, No. 4, pp. 613–622, 2004. **Purpose:** To compare the ventilatory response of two incremental exercise tests and determine their predictive validity on 40-km cycle time trial (40K) mean power output ($40K_{avgwatts}$). **Methods:** Fifteen male cyclists performed two incremental exercise tests (T_{50x3}:100 W +50 W·3 min^{-1}, T_{25x1}:20 W + 25 W·min^{-1}) and a 40K over an 8-d period. Key variable was power at ventilatory threshold (VT). For VT determination during each test we used: $\dot{V}E/\dot{V}O_2$ method, first clear breakpoint on the $\dot{V}E/\dot{V}CO_2$ plot, V-slope method, RER = 1, and RER = 0.95. **Results:** $\dot{V}O_{2max}$ during T_{50x3} and T_{25x1} was not different (66.6 vs 67.6 mL·kg^{-1}·min^{-1}), although T_{25x1} peak power output ($MaxT_{25x1}$; 402 W) was significantly higher than $MaxT_{50x3}$ (363 W). T_{50x3} and T_{25x1} VT power outputs indicated that the power output at T_{25x1}:RER = 1 and T_{25x1}:RER = 0.95 were significantly higher compared with T_{50x3} (324 vs 304 W and 282 vs 264 W, respectively). Regression analyses between T_{50x3} variables and $40K_{avgwatts}$ were significant for T_{50x3}:V-slope (R^2 = 0.37; SEE 20.2 W), T_{50x3}:$\dot{V}E/\dot{V}O_2$ (R^2 = 0.64; SEE 15.3 W), T_{50x3}:RER = 0.95 (R^2 = 0.42; SEE 19.4 W), T_{50x3}:RER = 1 (R^2 = 0.45; SEE 18.8 W), and $MaxT_{50x3}$ (R^2 = 0.51; SEE 17.8 W). Regression analyses between T_{25x1} variables and $40K_{avgwatts}$ were significant for T_{25x1}:V-slope (R^2 = 0.63; SEE 15.4 W), T_{25x1}:$\dot{V}E/\dot{V}O_2$ (R^2 = 0.64; SEE 15.2 W), T_{25x1}:RER = 0.95 (R^2 = 0.53; SEE 17.4 W), T_{25x1}:RER = 1 (R^2 = 0.57; SEE 16.7 W), and $MaxT_{25x1}$ (R^2 = 0.65; SEE 15.0 W). There was no significant difference between $40K_{avgwatts}$ (282 W) and power outputs at T_{50x3}:$\dot{V}E/\dot{V}O_2$ (277 W), T_{50x3}:V-slope (289 W), T_{25x1}:$\dot{V}E/\dot{V}O_2$ (276 W), and T_{25x1}:RER = 0.95 (282 W). **Conclusion:** Generally, T_{25x1} based VT variables were superior to T_{50x3} variables regarding the prediction of $40K_{avgwatts}$. We conclude that the $\dot{V}E/\dot{V}O_2$ method is protocol independent and a valid $40K_{avgwatts}$ predictor. **Key Words:** TESTING, POWER OUTPUT, TRAINING, PERFORMANCE PREDICTION, CYCLING TIME TRIAL

The performance threshold (PT) (also, yet inappropriately, referred to as "anaerobic threshold"), based on the analysis of an incremental exercise test, can be used to predict endurance performance (7,22). The PT can be determined by either lactate or ventilatory assessment of the appropriate physiological response during an incremental exercise test. A wide variety of diagnostic criteria can be found in the literature for both, ventilatory threshold (VT) and lactate threshold (LT) assessment. A recent study from our laboratory (unpublished data) indicated the superiority of ventilatory assessment over lactate assessment regarding the prediction of power output at PT for cyclists. At present, different protocols are used to determine VT and LT. Power output increments of 10–30 W and durations of 30–60 s are often used for VT assessment (2,7,8,16,27). This is mainly due to the enhanced sensitivity for detection of the isocapnic buffering period while using shorter stage durations (27) and short time (<1 min) to reach equilibrium (24). Nevertheless, Whipp and Wasserman (29) suggested an equilibrium time of approximately 3 min for $\dot{V}O_2$. In comparison with gas exchange, the changes in blood lactate concentration after an increase in workload is delayed. Thus, it is necessary to have a longer stage duration during LT tests. Workload increments of 9–50 W are common in LT tests (2,8,12,15), each of which requires a specific time to reach equilibrium (21). According to Stockhausen et al. (21), Heck (12), and Mader et al. (17), a stage duration between 6 and 10 min is necessary to reach an equilibrium between arterial blood lactate and muscle lactate concentration. However, according to Kindermann et al. (15), a workload duration of 3 min is sufficient for the assessment of LT (although equilibrium is not reached yet), and longer stages only increase laboratory time and reduce $\dot{V}O_{2max}$. Two widely used protocols for PT assessment are: 20 W + 25 W·min^{-1} (16) for VT analysis and 100 W + 50 W·3 min^{-1} (23) for LT analysis. The purpose of this study was to compare the ventilatory responses resulting from the two different incremental stage tests. In addition, we evaluated and compared their predictive validity for 40-km cycling time trial (40K) performance. The goal was to identify a laboratory tests that can be used to predict 40K performance with much less effort from the subject than a full out competitive time trial.

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TABLE 1. Mean values and standard deviations of the subject's anthropometric and training history data; $N = 15$.

Age (yr)	Body Mass (kg)	Height (cm)	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	Years of Training	Years of Racing	km·yr^{-1}	h·yr^{-1}	USA Cycling Category
31.5 ± 8.5	70.2 ± 8.2	175.1 ± 5.2	67.6 ± 5.3	9.3 ± 4.4	7.3 ± 3.3	14000 ± 5400	667 ± 182	I–II

METHODS

Subjects. Fifteen experienced male road cyclists (Table 1) volunteered for this investigation. Written informed consent was obtained from each participant as directed by the institution's human subjects research committee.

Study protocol. For 3 d before and during the study, subjects followed a high-carbohydrate (CHO) diet (9–10 g CHO per kg body weight). For 24 h before testing sessions, subjects were instructed to avoid strenuous physical activity, including high volume and/or intensity training sessions. A practice 40K was performed by the subject 1 wk before the beginning of the study.

Two different incremental stage tests (T_{50x3}: 100 W + 50 W·3 min^{-1}, T_{25x1}: 20 W + 25 W·min^{-1}; Fig. 1), separated by 48 h, were performed by each subject over a 3-d period. T_{50x3} and T_{25x1} were performed in random order. Order effects could be excluded because eight subjects started with T_{50x3} and seven subjects started with T_{25x1}. The 40K was performed after a 72-h recovery period. All tests were performed on an electrically braked cycle ergometer (Velotron Electronic Bicycle Ergometer, Elite Model, Racer Mate, Seattle, WA) that was modified with a racing saddle, adjustable stem, and the subject's pedal system. Velotron is a computer-controlled, electronic bicycle of a proprietary new design (patent pending) with associated interactive Windows PC software. Distance, speed, and workload (considering body weight) are calculated electronically. The design uses an eddy current brake built around a heavy (55 lb), large-diameter flywheel with an internal freewheel. Subjects' personal gear ratios can be entered. The shifting is accomplished electronically through the PC control software during the time trial.

Warm-up program. Two different 30-min warm-up protocols were used in this study: 1) for T_{50x3} and T_{25x1}, the subjects performed a 15-min individual (IW: any preferred workload ≤ 150 W) immediately followed by a 15-min standardized (SW; at 1.5 W × body weight in kilograms) warm-up protocol; and 2) For the 40K, subjects followed the SW protocol for 10 min, followed by the IW protocol for 15 min. The IW protocol for the 40K included three 1-min sprints (5th, 10th, and 15th minutes) at any preferred workload. The warm-up period for the 40K was concluded by 5 min of SW. Subjects were allowed to cycle at any preferred pedal cadence throughout the warm-up period.

Test protocol 1 (T_{50x3}). T_{50x3} started at a power output of 100 W and was increased every 3 min by 50 W (23) until exhaustion or when pedal cadence dropped below 70 rpm. Heart rate data were collected throughout the test via telemetry (S810, Polar Instruments Inc., Oulu, Finland). Gas exchange data were collected continuously using open-circuit spirometry (ParvoMedics, True Max 2400, Sandy, UT), and respiratory data were averaged for 20-s periods. Peak power output ($MaxT_{50x3}$) was computed as follows: $W_{peak} = W_f + [(t/D \times P)]$, where W_f was the value of the last completed workload (W), t was the time (s) the last uncompleted workload was maintained, D was the duration (s) of each stage, and P was the power output difference between workloads (1). Subjects were allowed to cycle at any preferred cadence between 70 and 120 rpm. Instructions were given to keep the rpm at their preferred pedal cadence throughout the whole test.

Test protocol 2 (T_{25x1}). T_{25x1} started at a power output of 20 W and the workload was increased by 25 W·min^{-1} to exhaustion (16). The test was terminated when minimum pedal cadence could not be maintained at 70 rpm. Heart rate and gas exchange data were collected continuously. For both T_{50x3} and T_{25x1}, $\dot{V}O_{2max}$ was recorded as the highest $\dot{V}O_2$ value obtained over a 20-s averaging period. The peak power output ($MaxT_{25x1}$) was computed as described above. Subjects were allowed to cycle at any preferred cadence between 70 and 120 rpm. Instructions were given to keep the rpm at their preferred pedal cadence throughout the whole test.

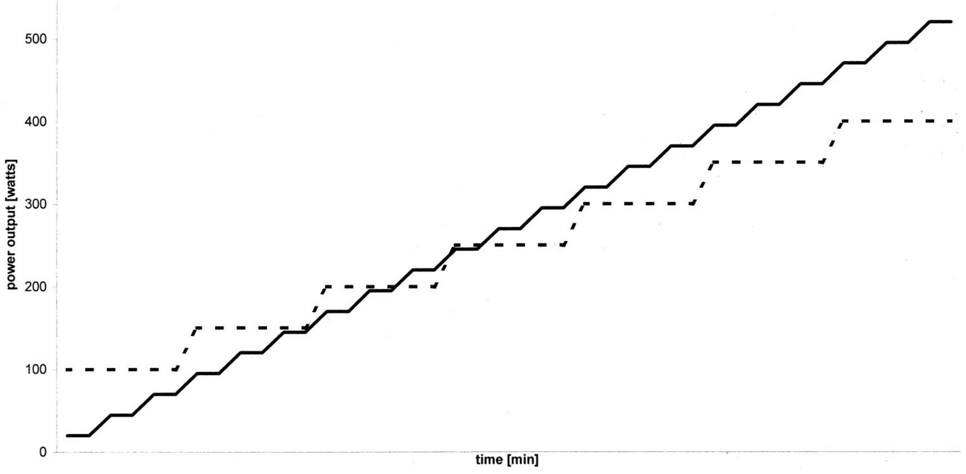

FIGURE 1—Incremental stage testing protocols utilized in this study (*dashed line*, T_{50x3}: 100 W ± 50 W·3 min^{-1}; *solid line*, T_{25x1}: 20 W ± 25 W·min^{-1}).

TABLE 2. Comparison of $T_{50\times3}$ and $T_{25\times1}$ variables (paired *t*-tests, $\alpha = 0.05$); (mean values ± SD).

	Power Output (W)			$\dot{V}O_2$ ($mL\cdot kg^{-1}\cdot min^{-1}$)		
	$T_{50\times3}$	$T_{25\times1}$	*P*	$T_{50\times3}$	$T_{25\times1}$	*P*
Peak	363 ± 29	402 ± 35*	<0.01	66.6 ± 5.6	67.6 ± 5.3	NS
V-slope	289 ± 33	297 ± 34	NS	55.7 ± 5.2	55.0 ± 6.5	NS
$RER_{1.0}$	304 ± 41	325 ± 39*	<0.01	58.4 ± 6.4	58.2 ± 6.6	NS
$RER_{0.95}$	264 ± 44	282 ± 35*	<0.05	52.5 ± 7.1	52.3 ± 6.3	NS
$\dot{V}E/\dot{V}O_2$	277 ± 32	276 ± 40	NS	55.0 ± 4.6	50.4 ± 6.7*	<0.01
$\dot{V}E/\dot{V}CO_2$	277 ± 39	292 ± 33	NS	55.4 ± 5.3	54.6 ± 4.2	NS
Time to exhaustion [min:s]	19:12 ± 1:42	16:24 ± 1:30*	<0.01			

* Significantly different from corresponding $T_{50\times3}$ condition.

40-km time trial. During the 40K, $\dot{V}O_2$ measurements were taken every 5 km for 2 min, and heart rate was recorded continuously. 40K performance variables were time to completion ($40K_{time}$) and mean power output ($40K_{avgwatts}$). The subjects were free to regulate their workload either by pedaling cadence or gearing, just as they would on a real cycle in a real competition. The only instruction to the subject was to finish in minimal time, just as in competition. The subjects were given full feedback regarding distance completed and time.

Ventilatory threshold identification. Five common methods were used to identify the power output at ventilatory threshold: 1) the power output at which the respiratory exchange ratio equals 1 ($RER_{1.0}$) (27) and 2) RER = 0.95 ($RER_{0.95}$) (26); 3) ventilatory equivalent method ($VE/\dot{V}O_2$): the power output corresponding with a systematic increase in the ventilatory equivalent of oxygen ($\dot{V}E/\dot{V}O_2$) without a concomitant increase in the ventilatory equivalent of carbon dioxide ($\dot{V}E/\dot{V}CO_2$) (25); 4) V-slope-method: the power output at which a clear steeper increase of $\dot{V}CO_2$ as compared with $\dot{V}O_2$ occurs (3; as described in 13); and 5) $\dot{V}E/\dot{V}CO_2$ method: the power output at which a first clear breakpoint on the $\dot{V}E/\dot{V}CO_2$ plot can be seen ($\dot{V}E/\dot{V}CO_2$) (6).

Statistical analysis. Paired *t*-tests were used to evaluate differences between T_{50x3} and T_{25x1} variables. Regression analyses were performed to compare key variables

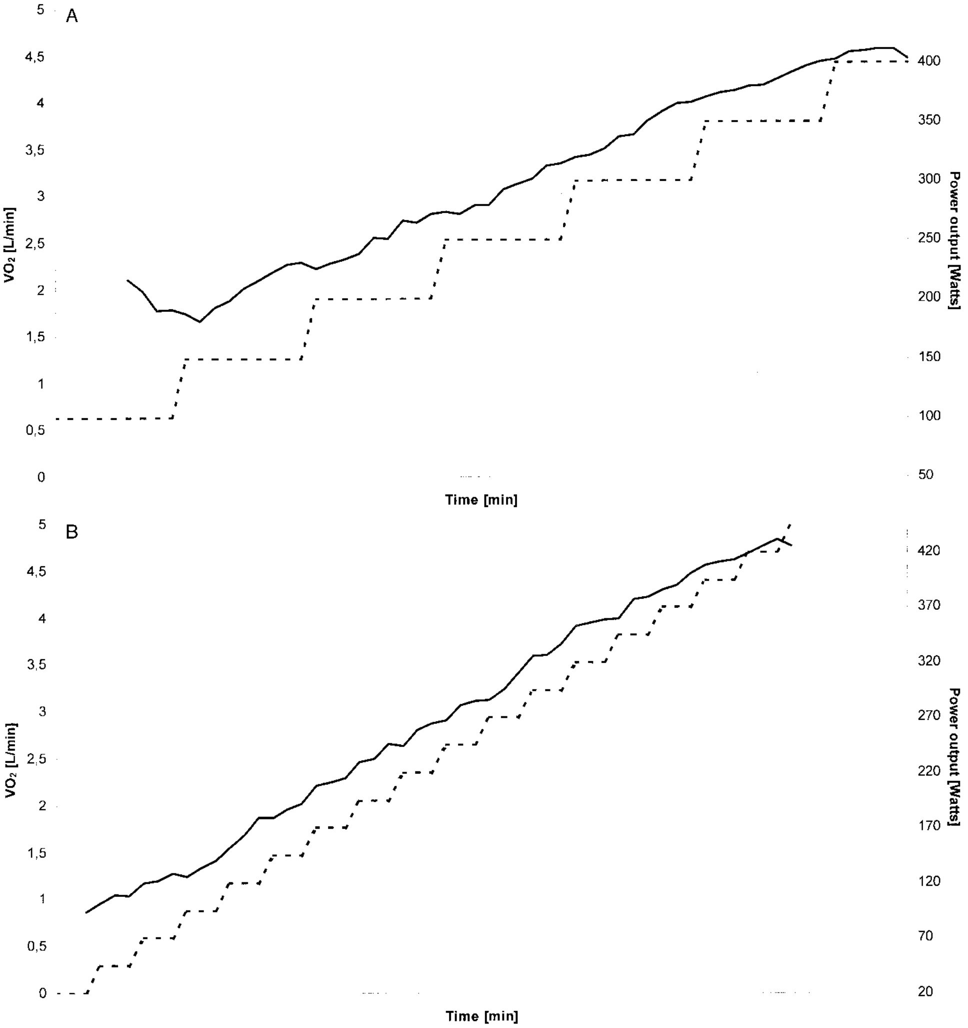

FIGURE 2—Characteristic of operating sequence (*dashed line*) and the resulting $\dot{V}O_2$ response (*solid line*): a) T_{50x3}, b) T_{25x1}.

obtained during T_{50x3} (power output at: $MaxT_{50x3}$, T_{50x3}: $\dot{V}E/\dot{V}O_2$, T_{50x3}:V-slope, T_{50x3}:$\dot{V}E/\dot{V}CO_2$, T_{50x3}:$RER_{1.0}$, T_{50x3}:$RER_{0.95}$) and T_{25x1} (power output at: $MaxT_{25x1}$, T_{25x1}: $\dot{V}E/\dot{V}O_2$, T_{25x1}:V-slope, T_{25x1}:$\dot{V}E/\dot{V}CO_2$, T_{25x1}:$RER_{1.0}$, T_{25x1}:$RER_{0.95}$) versus $40K_{avgwatts}$. Differences between power output from the predictive tests (T_{50x3}, T_{25x1}) with significant regression analyses and $40K_{avgwatts}$ were evaluated using paired *t*-tests ($\alpha = 0.25$).

RESULTS

Table 2 represents the results of the comparison between T_{50x3} and T_{25x1} variables. A paired *t*-test between $\dot{V}O_{2max}$ at T_{50x3} (66.6 ± 5.6 $mL \cdot kg^{-1} \cdot min^{-1}$) and T_{25x1} (67.6 ± 5.3 $mL \cdot kg^{-1} \cdot min^{-1}$) indicated no significant difference ($P = 0.299$), although $MaxT_{25x1}$ (402 ± 35 W) was significantly greater than $MaxT_{50x3}$ (363 ± 29 W) (paired *t*-test, $P < 0.01$). Time to exhaustion was significantly shorter (16:24 ± 1:30 min vs 19:12 ± 1:42 min) for T_{25x1} as compared with T_{50x3}. Paired *t*-tests with T_{50x3} and T_{25x1} VT power outputs (V-slope, $RER_{1.0}$, $RER_{0.95}$, $\dot{V}E/\dot{V}O_2$, $\dot{V}E/\dot{V}CO_2$) indicated that the wattages for T_{25x1}:$RER_{1.0}$ and T_{25x1}: $RER_{0.95}$ were significantly higher compared with T_{50x3} conditions ($P < 0.01$ and $P < 0.05$, respectively). When expressed as the corresponding $\dot{V}O_2$, the only significant difference was found between T_{50x3}:$\dot{V}E/\dot{V}O_2$ and T_{25x1}:$\dot{V}E/\dot{V}O_2$ ($P < 0.01$).

The results of the regression analyses between the predictor variables and $40K_{avgwatts}$ are illustrated in Table 3 and Figures 3 and 4. The correlations were generally stronger with T_{25x1} derived variables including T_{25x1}:$\dot{V}E/\dot{V}O_2$, T_{25x1}: V-slope, and $MaxT_{25x1}$. A similar strong correlation was observed for the predictor variable T_{50x3}:$\dot{V}E/\dot{V}O_2$, whereas the remaining T_{50x3} and T_{25x1} variables only showed a moderate correlation. The regression analyses for the predictor variable $\dot{V}E/\dot{V}CO_2$ was not significant for either T_{50x3} or T_{25x1}. Paired *t*-tests between the variables with a significant regression analysis and $40K_{avgwatts}$ indicated that T_{50x3}:$\dot{V}E/\dot{V}O_2$ ($P = 0.326$), T_{50x3}:V-slope ($P = 0.329$), $_{T25x1}$:$\dot{V}E/\dot{V}O_2$ ($P = 0.334$), and T_{25x1}:$RER_{0.95}$ ($P = 0.933$) were not significantly different from $40K_{avgwatts}$.

DISCUSSION

The first goal of this study was to evaluate and compare two widely used incremental stage protocols, both of which

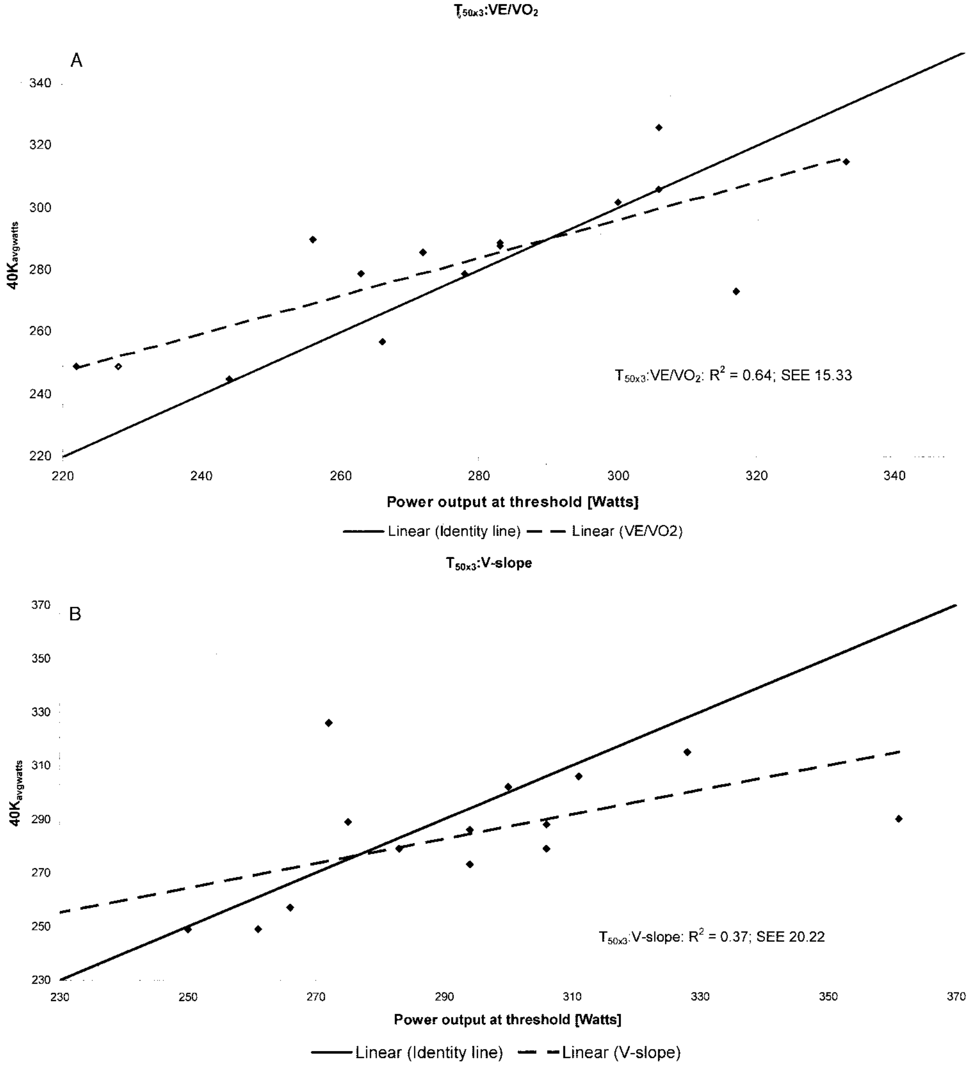

FIGURE 3—Relationship between T_{50x3} variables of interest and $40K_{avgwatts}$: a) T_{50x3}:$\dot{V}E/\dot{V}O_2$, b) T_{50x3}:V-slope, c) T_{50x3}:$RER_{1.0}$, d) T_{50x3}:$RER_{0.95}$, e) T_{50x3}: $\dot{V}E/\dot{V}CO_2$, f) $MaxT_{50x3}$.

TABLE 3. Squared correlations (R^2) and correlations (r) between variables of interest and $40K_{avgwatts}$; 95% confidence limits (CL) for pearson correlations [using internet spread sheet by Hopkins and McKenzie (14)]; standard error of estimate (SEE, in watts) and regression equations; *P* values: paired *t*-tests between variables and $40K_{avgwatts}$; $N = 15$.

	R^2	r	95% CL	SEE	*P*	Regression Equation
$T_{50\times3}$						
$T_{50\times3}$: $\dot{V}E/\dot{V}O_2$	0.64***	0.80	0.49–0.93	15.3 W	0.326	$y = 0.613x + 112.32$
$T_{50\times3}$: $RER_{0.95}$	0.42**	0.65	0.21–0.87	19.5 W	0.057	$y = 0.3618x + 186.62$
$T_{50\times3}$: $RER_{1.0}$	0.45**	0.67	0.24–0.88	18.9 W	0.017	$y = 0.401x + 160.4$
$T_{50\times3}$: V-slope	0.37*	0.61	0.14–0.86	20.2 W	0.329	$y = 0.4576x + 149.93$
$T_{50\times3}$: $\dot{V}E/\dot{V}CO_2$	NS					
$MaxT_{50\times3}$	0.51**	0.71	0.31–0.90	17.8 W	0.000	$y = 0.6132x + 59.681$
$T_{25\times1}$						
$T_{25\times1}$: $\dot{V}E/\dot{V}O_2$	0.64***	0.80	0.49–0.93	15.2 W	0.334	$y = 0.4886x + 147.52$
$T_{25\times1}$: $RER_{0.95}$	0.53**	0.73	0.35–0.90	17.4 W	0.933	$y = 0.5054x + 139.84$
$T_{25\times1}$: $RER_{1.0}$	0.57**	0.75	0.39–0.91	16.8 W	0.000	$y = 0.4695x + 129.82$
$T_{25\times1}$: V-slope	0.63***	0.79	0.47–0.93	15.5 W	0.014	$y = 0.5819x + 109.32$
$T_{25\times1}$: $\dot{V}E/\dot{V}CO_2$	NS					
$MaxT_{25\times1}$	0.65***	0.81	0.51–0.93	15.0 W	0.000	$y = 0.5641x + 55.539$

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

are commonly used to determine PT, with regard to their ventilatory response and VT assessment capability. T_{50x3} is traditionally utilized for lactate threshold assessment, whereas T_{25x1} has been used widely for VT analyses. The second goal was to compare and validate the power output at VT based on the analysis of both protocols using different VT assessment methods against $40K_{avgwatts}$.

Evaluation of protocols. In the present study, $\dot{V}O_{2max}$ was not significantly different between T_{50x3} and T_{25x1}. These findings agree with previous reports (9,18,28) suggesting that $\dot{V}O_{2max}$ is substantially the same during incremental cycle ergometer exercise testing regardless of the rate of work increase during ramp-pattern testing. A previously published study (18) with well-trained rowers indicates that longer testing protocols can provide valid measurements for $\dot{V}O_{2max}$. According to these findings, both protocols are appropriate for $\dot{V}O_{2max}$ assessment, and thus, as a consequence, T_{50x3} and T_{25x1} $\dot{V}O_{2max}$ did not signifi-

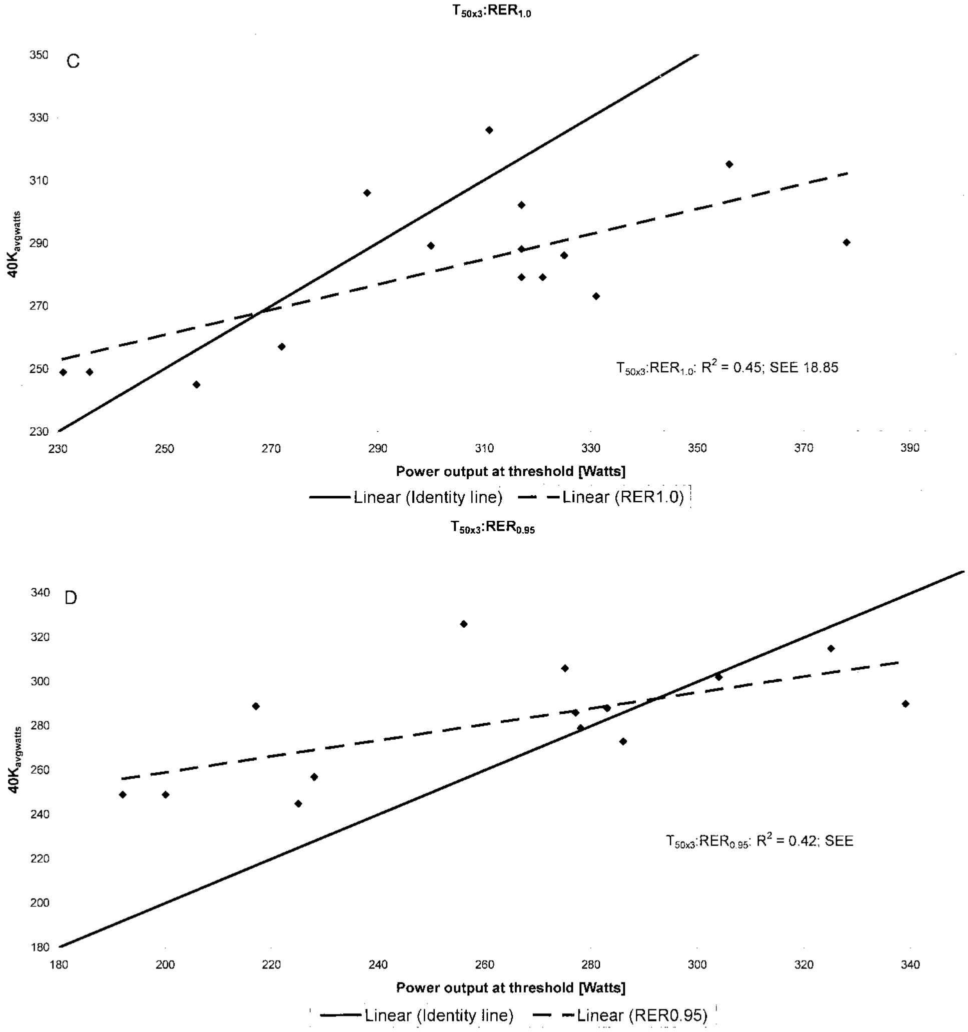

FIGURE 3—Continued.

cantly differ. Our findings are in contrast to Buchfuhrer et al.'s (5) report indicating that longer test durations lead to lower $\dot{V}O_{2max}$ values, which might be due to an increased thermoregulatory load, greater dehydration, or ventilatory muscle fatigue.

The absolute values for $\dot{V}O_2$ at the various VT are listed in Table 2. In our study, $\dot{V}O_2$ at $\dot{V}E/\dot{V}O_2$ was the only VT influenced by different test protocols. Other investigators have also reported no difference in oxygen uptake at VT measured during different incremental (19) or ramp function tests (9,28). T_{25x1}:$\dot{V}E/\dot{V}O_2$ absolute oxygen uptake was significantly ($P < 0.01$) lower than T_{50x3}:$\dot{V}E/\dot{V}O_2$, with the relative values of 83% and 75% $\dot{V}O_{2max}$ for T_{50x3} and T_{25x1}, respectively. Because the actual values of T_{25x1}:$\dot{V}E/\dot{V}O_2$ (26.3 ± 3.0) and T_{50x3}:$\dot{V}E/\dot{V}O_2$ (27.1 ± 2.5) were not significantly different ($P = 0.19$), $\dot{V}E$ was logically higher at T_{50x3}:$\dot{V}E/\dot{V}O_2$ (106.9 ± 15.2 $L \cdot min^{-1}$) compared with T_{25x1}:$\dot{V}E/\dot{V}O_2$ (93.5 ± 20.0 $L \cdot min^{-1}$) ($P < 0.01$). Major stimuli for $\dot{V}E$ are provided by the central chemoreceptors, mostly influenced by PCO_2 (24), as well as peripheral chemoreceptors, influenced by $[H^+]$, $[K^+]$, catecholamines and increased body temperature. Central and/or peripheral neurogenic control also influence $\dot{V}E$ and can be linked to muscular fatigue (24). The different $\dot{V}E$ during T_{25x1} and T_{50x3} suggest that different power increments and stage durations influence $\dot{V}E$ in different manners resulting in the occurrence of $\dot{V}E/\dot{V}O_2$ at different $\dot{V}O_2$. On average, T_{25x1}:$\dot{V}E/\dot{V}O_2$ occurred after 11 min, whereas T_{50x3}:$\dot{V}E/\dot{V}O_2$ did not occur until 13.5 min.

The absolute power output at VT assessed by $\dot{V}E/\dot{V}O_2$, $\dot{V}E/\dot{V}CO_2$, and V-slope were not affected by the different protocols (Table 2). However, Ribeiro et al. (19) reported higher power output values at VT for a protocol with increments of 15 W every 15 s compared with 15 W every minute, when using the $\dot{V}E/\dot{V}CO_2$ method. This finding might be explained by the short stage duration (15 s) during the fast protocol, which does not account for the 30–40 s necessary to stabilize gas exchange and ventilatory response (24). Due to the significant changes in peak power output with different test protocols, relative power output at VT decreased from 80% to 74% (V-slope), 76% to 68% ($\dot{V}E/\dot{V}O_2$), and 76% to 73% ($\dot{V}E/\dot{V}CO_2$) for T_{50x3} and T_{25x1}, respectively. The duration of the step increment and the increments in power output may account, therefore, for

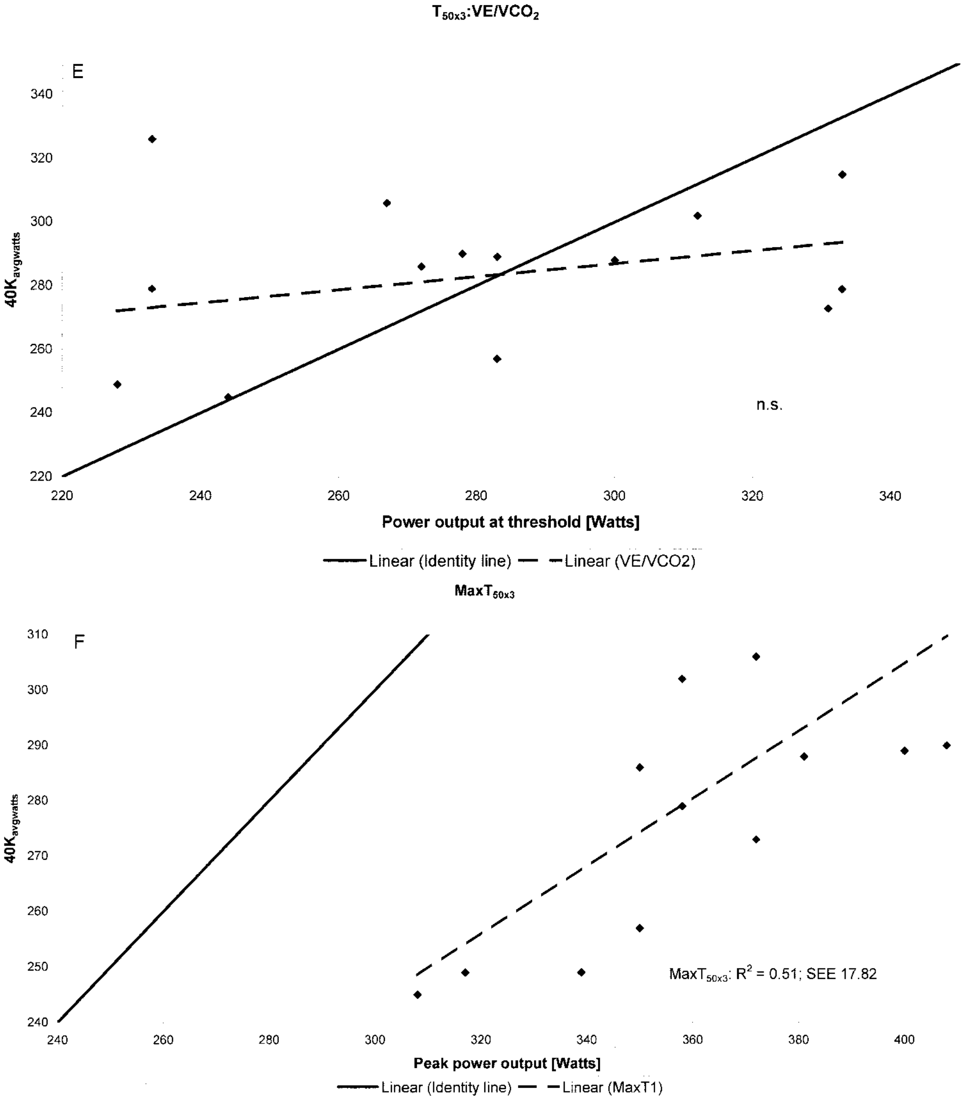

FIGURE 3—Continued.

some of the variability in relative VT power outputs reported in the literature. When expressed as absolute power output, $\dot{V}E/\dot{V}O_2$, $\dot{V}E/\dot{V}CO_2$, and V-slope are independent from the testing protocol and represent individual methods of PT assessment.

The absolute power output at $RER_{1.0}$ and $RER_{0.95}$ was influenced by the test protocol and was significantly higher during T_{25x1} ($P < 0.01$ and $P < 0.05$, respectively). Due to the significantly higher peak power output during T_{25x1}, relative power outputs (relative to respective peak power output) for the fixed RER decreased from 83.7% to 80.8% ($RER_{1.0}$) and from 72.8% to 70.1% ($RER_{0.95}$) during T_{50x3}. Both the absolute and the relative power output at a fixed RER are protocol dependent and therefore not suitable for an individual VT assessment tool. If used, protocol-dependent, power output at a fixed RER may still be accepted as a measurement of the change of endurance ability over time, similar to PT assessment through a fixed lactate concentration (e.g., power output at a blood lactate concentration of 4 $mmol \cdot L^{-1}$).

Despite the similar $\dot{V}O_{2max}$, the average peak power output during T_{50x3} (362.9 ± 28.6 W) was significantly lower ($P < 0.01$) than during T_{25x1} (401.8 ± 35.1 W), and the average test duration for T_{50x3} (19.2 ± 1.7 min) was significantly longer ($P < 0.01$) than for T_{25x1} (16:24 ± 1:30 min). This phenomenon might be explained by the different increments in workload over time ($\Delta W/\Delta t$). During T_{50x3} $\Delta W/\Delta t$ was about 16.7 $W \cdot min^{-1}$, during T_{25x1} $\Delta W/\Delta t$ was 25 $W \cdot min^{-1}$. T_{25x1} $\Delta W/\Delta t$ is steeper and results in a more rapid increase in $\dot{V}O_2$ (Fig. 2). Due to these steeper increases during T_{25x1} ($\Delta W/\Delta t$ and, as a consequence, $\dot{V}O_2$ over time), an athlete's maximal endurance capability ($\dot{V}O_{2max}$) is reached faster and at a higher peak power output, and thus, the test duration is shorter. An additional explanation for the significantly lower $MaxT_{50x3}$ might be the absolute accumulated external mechanical work performed by a subject at a certain similar workload. At a power output of 300 W (T_{50x3}: 15 min into the test, T_{25x1}: 12:12 min into the test), a subject already performed 54.0 kJ of external work in T_{50x3} versus 18.0 kJ in T_{25x1}. The disproportionately higher accumulated external work performed at a similar workload during T_{50x3} leads to the significant lower maximal power output at the end of the test, when $\dot{V}O_{2max}$ is reached, as compared with T_{25x1}. This might be due to fatigue.

Evaluation of predictive validity. Although changes in work rate and test duration appear to have little effect on $\dot{V}O_2$ (5,9) and power output (Table 3; apart from RER) at VT, there is still disagreement as to the optimal rate of

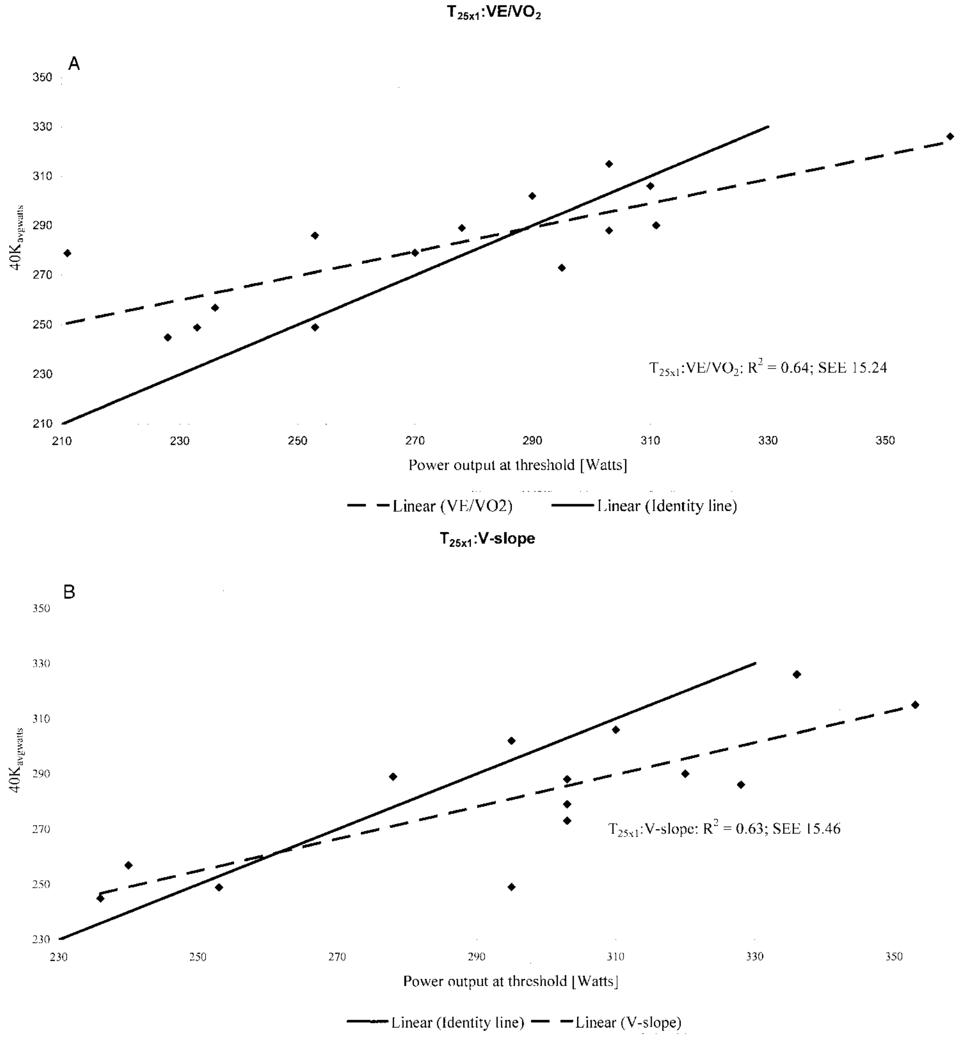

FIGURE 4—Relationship between T_{25x1} variables of interest and $40K_{avgwatts}$: a) T_{25x1}:$\dot{V}E/\dot{V}O_2$, b) T_{25x1}:V-slope, c) T_{25x1}:$RER_{1.0}$, d) T_{25x1}:$RER_{0.95}$, e) T_{25x1}:$\dot{V}E/\dot{V}CO_2$, f) $MaxT_{25x1}$.

change in work rate and time required to identify the PT. It is conceivable that a given increment in work rate as large as 25–50 W could artificially produce ventilatory changes that could be interpreted as the PT, whereas the actual PT lies somewhere in between. The conflicting observation that $\dot{V}O_2$ at VT varies significantly depending on the method of detection or the exercise protocol (10,20), along with the present results that power output at VT varies depending on the method of detection (Table 3), suggests that the variety of noninvasively detected PT needs to be validated against a prolonged high-intensity performance. In other words, even though T_{50x3} and T_{25x1} power output, assessed by a certain PT assessment method, do not statistically differ, their practical validity in defining $40K_{avgwatts}$ might be different and a comparison of means between power outputs at thresholds and $40K_{avgwatts}$ might indicate a significant difference.

In the literature, VT appears to be highly correlated to various types of endurance performance (13) and can therefore be considered as potentially reliable for performance prediction. In this study, the power outputs for T_{25x1} based variables were overall better correlated with 40K performance (Table 3). The correlation coefficients for T_{25x1} based variables and $40K_{avgwatts}$ ranged between 0.73 and 0.81. This range is comparable with other studies reporting correlations of 0.75 to 0.82 between VT variables and actual endurance performance (13). The strongest correlations were computed with T_{25x1}:$\dot{V}E/\dot{V}O_2$, T_{25x1}:V-slope, and $MaxT_{25x1}$. A similar strong correlation was observed for the predictor variable T_{50x3}:$\dot{V}E/\dot{V}O_2$, whereas the remaining T_{50x3} and T_{25x1} variables only showed a moderate correlation with $40K_{avgwatts}$. The regression analyses for the predictor variable $\dot{V}E/\dot{V}CO_2$ was neither significant under T_{50x3} nor under T_{25x1} condition.

A wide variety of studies report the relationship between VT variables and an actual high-intensity cycling performance regarding $\dot{V}O_2$, HR (13), and power output (14). Typically, most investigations only report correlation coefficients (r) and do not compare the actual absolute power output at VT with $40K_{avgwatts}$ using a paired *t*-test. However, r only measures the strength of a relationship between two variables, not the absolute agreement between them. A major criteria for a certain VT assessment method to be considered as a valid PT measurement in this study was therefore not only a high r but also a nonsignificant paired *t*-test result against $40K_{avgwatts}$. Out of the variety of applied

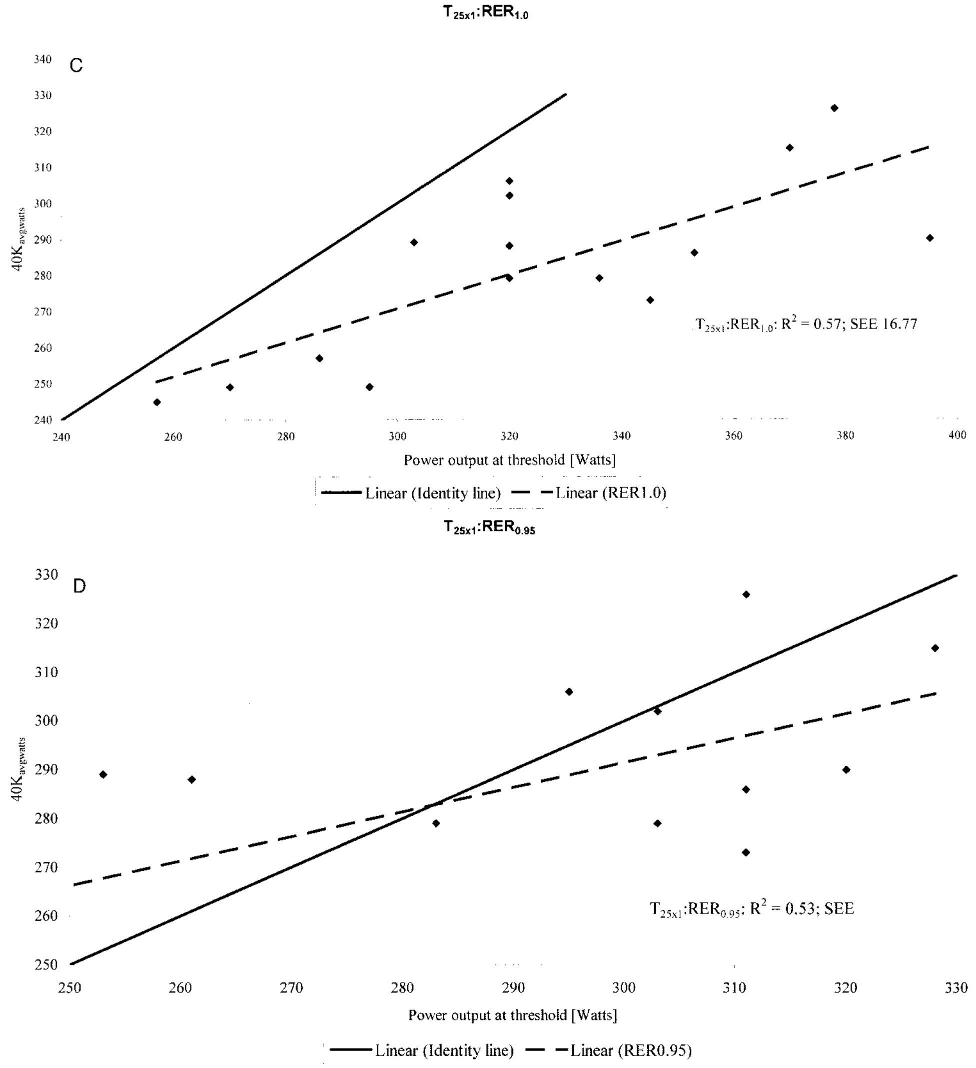

FIGURE 4—Continued.

PT assessment methods, only T_{50x3}:$\dot{V}E/\dot{V}O_2$, T_{50x3}:V-slope, T_{25x1}:$\dot{V}E/\dot{V}O_2$, and T_{25x1}:$RER_{0.95}$ met this criteria (Table 3). The group's overall $40K_{avgwatts}$ was 282.2 ± 24.55 W. The group's overall mean power output at T_{50x3}:$\dot{V}E/\dot{V}O_2$, T_{50x3}:V-slope, T_{25x1}:$\dot{V}E/\dot{V}O_2$, and T_{25x1}:$RER_{0.95}$ corresponded to 98.2 ± 11.3%, 102.4 ± 11.6%, 97.7 ± 14.3%, and 99.8 ± 12.5%, respectively, to the group's $40K_{avgwatts}$. Reconsidering the r values in connection with the paired *t*-tests, only T_{50x3}:$\dot{V}E/\dot{V}O_2$, T_{25x1}:$\dot{V}E/\dot{V}O_2$, and T_{25x1}: $RER_{0.95}$ can be considered as valid $40K_{avgwatts}$ predictors.

$MaxT_{50x3}$ and $MaxT_{25x1}$ variables were essentially equal with VT variables in terms of predicting $40K_{avgwatts}$, although the absolute value of power output was, expectedly, quite different (Table 3). $MaxT_{50x3}$ and $MaxT_{25x1}$ were, as reported earlier, significantly ($P < 0.01$) different. A variety of previous studies have also shown the maximal power output (W_{peak}) obtained during an incremental cycle test to exhaustion is a valid and reliable indicator of endurance performance (1,4,11). Although, none of these studies examined the reliability and validity of W_{peak} during different incremental exercise protocols and the relationship to endurance performance differing by mode and duration, Bentley et al. (4) found that 83% of the variance in a 90 min TT was explained by W_{peak} when using a protocol starting with a workload corresponding to 50% of $\dot{V}O_{2max}$ and increases by 5% of $\dot{V}O_{2max}$ every 3 min. In the present study, 81% of the variance in the 40K was explained by $MaxT_{25x1}$ and 71% by $MaxT_{50x3}$. Balmer et al. (1) have reported a correlation coefficient of $r = 0.99$ between W_{peak} and the average power output during a 16.1 km TT. A similar negative relationship has also been reported between W_{peak} and the time taken to complete 20 km ($r = -0.91$) or 40 km ($r = -0.87$) (11). In our investigation, we found a correlation coefficient of $r = -0.81$ ($r = -0.73$) between $MaxT_{25x1}$ ($MaxT_{50x3}$) and the time taken to complete the 40K. For training management based on the assessment of coaches or athletes without the availability of a laboratory setting including a metabolic gas analyzer, we recommend using $MaxT_{25x1}$ to assess $40K_{avgwatts}$. The relationship between $MaxT_{25x1}$ and $40K_{avgwatts}$ is not simply a fixed percentage. For predicting the $40K_{avgwatts}$ (power output at PT) based on $MaxT_{25x1}$ we recommend assessing PT power output using the regression equation shown in Table 3 (PT = 0.5641·peak power output + 55.539 W).

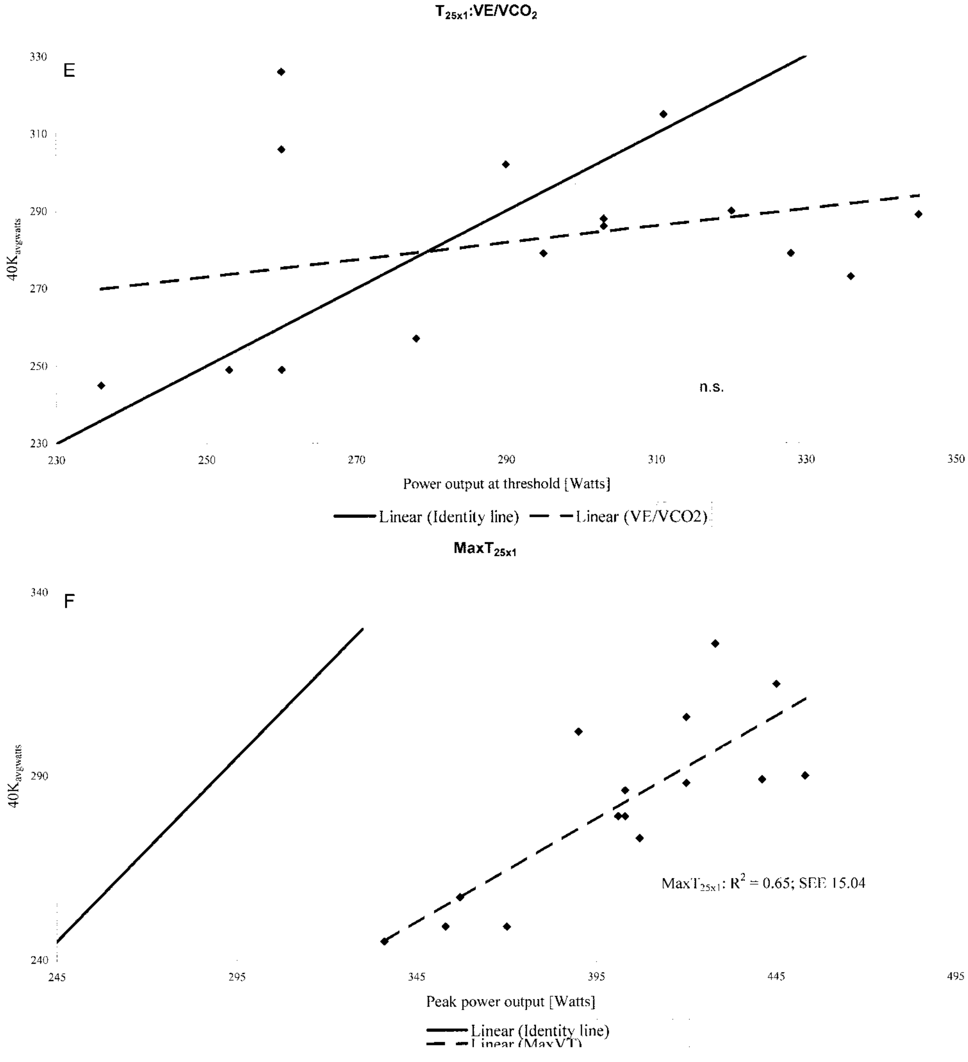

FIGURE 4—Continued.

SUMMARY

The most interesting result of the study was the similarity of T_{50x3}:$\dot{V}E/\dot{V}O_2$ and T_{25x1}:$\dot{V}E/\dot{V}O_2$ with regard to absolute power outputs and correlations with $40K_{avgwatts}$. In addition, both power outputs were not statistically different to $40K_{avgwatts}$. We recommend the use of $\dot{V}E/\dot{V}O_2$ as a valid and protocol independent method to assess PT power output. Also, T_{25x1} is of shorter duration as compared with T_{50x3} and an actual 40K in the lab and that way practically easier and of less effort for the athlete.

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