Reproducibility of the Cycling Time to Exhaustion at $\dot{V}O_2$peak in Highly Trained Cyclists

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Abstract/Résumé

The purpose of the present study was to examine, in highly trained cyclists, the reproducibility of cycling time to exhaustion (T_{max}) at the power output equal to that attained at peak oxygen uptake ($\dot{V}O_2$peak) during a progressive exercise test. Forty-three highly trained male cyclists (M ± SD; age = 25 ± 6 yrs; weight = 75 ± 7 kg; $\dot{V}O_2$peak = 64.8 ± 5.2 ml·kg^{-1} ·min^{-1}) performed two T_{max} tests one week apart. While the two measures of T_{max} were strongly related ($r = 0.884$; $p < 0.001$), T_{max} from the second test (245 ± 57 s) was significantly higher than that of the first (237 ± 57 s; $p = 0.047$; two-tailed). Within-subject variability in the present study was calculated to be 6 ± 6%, which was lower than that previously reported for T_{max} in sub-elite runners (25%). The mean T_{max} was significantly ($p < 0.05$) related to both the second ventilatory turnpoint (VT_2; $r = 0.38$) and to $\dot{V}O_2$peak ($r = 0.34$). Despite a relatively low within-subject coefficient of variation, these data demonstrate that the second score in a series of two T_{max} tests may be significantly greater than the first. Moreover, the present data show that T_{max} in highly trained cyclists is moderately related to VT_2 and $\dot{V}O_2$peak.

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Le but de cette étude est d'analyser, chez des cyclistes très bien entraînés, la reproductibilité du temps de performance jusqu'à épuisement à bicyclette (T_{max}) au cours d'une épreuve d'intensité égale à celle correspondant à la consommation d'oxygène de crête ($\dot{V}O_2$crête), consommation établie au cours d'un test d'intensité progressive. Quarante-trois cyclistes, tous des hommes, très bien entraînés (M ± é.t.; âge = 25 ± 6 ans, masse corporelle = 75 ± 7 kg; $\dot{V}O_2$crête = 64,8 ± 5,2 ml·kg^{-1}·min^{-1}), participent à deux T_{max} décalés de 7 jours. Bien que les deux performances soient étroitement reliées (r = 0,884; p < 0,001), T_{max} au deuxième test (245 ± 57 s) est significativement plus long que le premier (237 ± 57 s; p = 0,047; bilatéral). La variance intra dans cette étude (6 ± 6%) est plus faible que celle d'une étude récente faite chez des cyclistes de calibre inférieur (25%). T_{max} moyen (p < 0,05) est significativement corrélé au deuxième point d'inflexion ventilatoire (VT_2; r = 0,38) et au $\dot{V}O_2$crête (r = 0,34). Malgré un coefficient de variation plutôt faible, ces observations démontrent que le deuxième des résultats de T_{max} peut être significativement supérieur au premier. En outre, T_{max} chez des cyclistes très bien entraînés est peu relié à VT_2 et à $\dot{V}O_2$crête.

Introduction

The concept of exercise time to exhaustion (T_{max}) at the velocity at which maximal oxygen consumption ($\dot{V}O_2$max) is attained has been extensively examined in highly trained runners (Billat et al., 2000; Hill et al., 1997; Renoux et al., 2000), and also appears to be an effective means for prescribing high-intensity interval training (HIT) sessions in highly trained runners (Billat et al., 1996c; 1999; Smith et al., 1999). The reproducibility of T_{max} has been determined for runners: Billat et al. (1994b) measured T_{max} twice in 8 sub-elite runners, and found a correlation (r = 0.86; $p < 0.05$) between the two values (404 ± 101 vs. 402 ± 113 s). While the scores were not significantly different from each other, Billat et al. did report a high coefficient of variation of 25%.

The rationale for using T_{max} when prescribing a HIT program is based on the assumption that further improvements in $\dot{V}O_2$max in the highly trained athlete will only result from exercise training at or above $\dot{V}O_2$max (Laursen and Jenkins, 2002). Indeed, others have reported significant improvements in $\dot{V}O_2$max and running performance using HIT prescribed at specific fractions of T_{max} (Billat et al., 1999; 2001; Smith et al., 1999). While the physiological differences between the exercise modes of running and cycling are well known (Bijker et al., 2001; Boussana et al., 2001; Gavin and Stager, 1999), research has yet to determine the reproducibility of T_{max} in highly trained cyclists. Moreover, while T_{max} has been shown to be negatively related to both $\dot{V}O_2$max (Billat et al., 1994c; James and Doust, 2000) and running speed at $\dot{V}O_2$max (Billat et al., 1994c; 1995), as well as being positively related to measures of the anaerobic threshold in runners (Billat et al., 1994a; 1994b; Hill and Rowell, 1996), the relationship between these laboratory measured variables and T_{max} in cyclists remains unclear (Billat et al., 1996a).

Thus the main purpose of the present study was to assess the reproducibility of T_{max} at the peak oxygen uptake ($\dot{V}O_2$peak) cycling power output in highly trained male cyclists. A second purpose was to examine the relationships between T_{max} and laboratory measured variables.

Materials and Methods

SUBJECTS

Forty-three trained male athletes (cyclists and triathletes; *M* ± *SD* age = 25 ± 6 yrs; height = 180 ± 6 cm; mass = 75.1 ± 7.2 kg; sum of five skinfolds = 41.7 ± 15.0; $\dot{V}O_2$peak = 64.8 ± 5.2 ml·kg^{-1}·min^{-1}) were recruited for this study from several cycling and triathlon clubs during the off-season of their yearly training program. They had competed in competitive cycling events for 6 ± 4 years. After being fully informed of the risks associated with the study, the athletes completed a medical history questionnaire and gave their written informed consent to participate. The experimental protocol was approved by the Medical Research Ethics Committee of The University of Queensland. The subjects in this study also participated in three other studies that examined cycling performance in highly trained athletes (Laursen et al., 2002c; 2003; in press).

PROTOCOL

Testing Regimen. Before all tests, subjects were asked to keep their eating habits constant and to report to the laboratory at least 3 hrs postprandial. On the first day of testing they signed consent forms, and baseline measures of height, body mass, and sum of five skinfolds were taken. Skinfolds were measured in duplicate at five sites (bicep, tricep, subscapula, supraspinale, and abdomen) by the same researcher using Harpenden skinfold calipers (British Indicators, West Sussex, UK). Subjects were asked to maintain a detailed training diary throughout the data collection phase (285 ± 95 km·wk^{-1}). In the first week they reported to the laboratory (~21 °C, 40–60% RH, 760–770 mmHg) to undergo a progressive exercise test to exhaustion (see below) for the determination of peak oxygen consumption ($\dot{V}O_2$), as well as the power output associated with $\dot{V}O_2$peak (P_{max}). At least 24 hrs after the $\dot{V}O_2$peak test, and having not trained for at least 12 hrs, the subjects underwent their first T_{max} test at their P_{max}; this first test was considered a familiarisation trial (Hopkins, 2000). The T_{max} test was then repeated twice (performed 1 week apart), with the same provisions, in the following 2 weeks; each test was performed at the same time of day (Hill et al., 1998). The T_{max} data presented are the results of the final two tests only.

Progressive Exercise Test. $\dot{V}O_2$peak was determined on an electronically braked cycle ergometer (Lode Excalibur Sport, Quinton, Seattle, WA) modified with clip-in pedals and low-profile racing handlebars. The saddle and handle bar positions of the cycle ergometer were adjusted to resemble each subject's own bike, and subjects warmed up at their own pace for 5 min. Exercise began at a power output of 100 W; power output thereafter increased by 15 W every 30 s (Laursen et al., 2002a). Cyclists were permitted to maintain their preferred cadence, but the test was stopped when they were unable to maintain a cadence of more than 60 rpm. Expired air was analyzed for F_EO_2 and F_ECO_2 every 30 s during exercise (Ametek gas analysers; SOV S-3A11 and COV CD3A; Pittsburgh, PA). Minute ventilation ($\dot{V}_E$) was recorded every 30 s using a turbine ventilometer (Morgan, Model 096, Kent, UK).

The gas analyzers were calibrated immediately before and after each test using a certified beta gas mixture (Commonwealth Industrial Gas Ltd., Brisbane, Australia); the ventilometer was calibrated at pre- and postexercise using a 1-L syringe in accordance with the manufacturer's instructions. $\dot{V}O_2$peak during the incremental test was recorded as the highest $\dot{V}O_2$ reading averaged over two consecutive readings (Laursen et al., 2002c; Noakes, 1988). The first and second ventilatory thresholds (VT_1 and VT_2) were measured by two independent reviewers according to methods that have been recently described (Lucia et al., 2000b) and completed in our laboratory (Laursen et al., 2002a). Reviewers were blinded to each other's findings, and in the event of a disagreement, the opinion of a third reviewer was sought.

Time to Exhaustion (T_{max}). P_{max} was calculated from the progressive exercise test and defined as the power output that elicited a $\dot{V}O_2$ reading within 2.1 $ml \cdot kg^{-1} \cdot min^{-1}$ of the subsequent reading despite an increase in workload (i.e., 15 W in a 30-s period). This method of calculation is in accordance with calculations previously used in running studies (Billat and Koralsztein, 1996; Billat et al., 1996b; Smith et al., 1999). After a 5-min warm-up at 2 $W \cdot kg^{-1}$, subjects performed two 30- to 60-s bouts at 4 $W \cdot kg^{-1}$, separated by a 30-s recovery at 2 $W \cdot kg^{-1}$. Equipment was put in place and the subjects were then timed for the duration at which they could maintain P_{max} at a cadence above 60 $rev \cdot min^{-1}$ (i.e., T_{max}). Heart rate (HR) and $\dot{V}O_2$ were recorded at 20-s intervals throughout exercise. In order to be consistent with the $\dot{V}O_2$peak values obtained during the progressive exercise test, $\dot{V}O_2$peak during the T_{max} test was recorded as the highest $\dot{V}O_2$ reading averaged over three consecutive readings (Noakes, 1988). Following exercise, subjects were encouraged to cool-down at 50 W for 5 min.

Data Analysis. Mean values of the two T_{max} tests were compared using the Student *t*-test for paired samples; significance was set at an alpha level of 0.05 (two-tailed). Pearson product moment determined the relationships between the variables. Results are expressed as a mean ± *SD*.

Results

Tables 1 and 2 show the results from the $\dot{V}O_2$peak test and the two T_{max} tests, respectively. The mean P_{max} of the subjects used for both T_{max} tests was 408 ± 29 W. While the two values of T_{max} from these tests were related ($p < 0.001$; Figure 1), T_{max} from the second test differed from that of the first test (Table 2; $p = 0.047$), with relatively low variation and good agreement (Figure 2). There was no significant difference between $\dot{V}O_2$peak obtained during the first and second T_{max} tests (Table 2). In addition, the mean $\dot{V}O_2$peak measured during the T_{max} tests (4.83 ± 0.45 $L \cdot min^{-1}$) was not significantly different from that measured during the progressive cycle test (Table 1). While there was no difference in the peak heart rate (HR peak) obtained between the two T_{max} tests (Table 2), the mean value of the HR peak values (182 ± 10) was significantly lower than the HR peak recorded during the progressive cycle test (192 ± 11 bpm; $p < 0.001$). Percent HR peak obtained during the T_{max} test was partly related to the duration of the T_{max} test ($r = 0.22$; $p < 0.05$). Mean T_{max} (s) was related ($p < 0.05$) to both VT_2 ($L \cdot min^{-1}$; $r = 0.38$) and $\dot{V}O_2$peak ($L \cdot min^{-1}$; $r = 0.34$), but not to VT_1 ($r = 0.13$) or P_{max} ($r = 0.14$; both $p > 0.05$).

Table 1 Measured Variables During Progressive Cycle Ergometry (*N* = 43)

$\dot{V}O_2$peak ($L \cdot min^{-1}$)	HR peak (bpm)	PPO (W)	VT_1 ($L \cdot min^{-1}$)	VT_2 ($L \cdot min^{-1}$)	RER peak
4.84 ± 0.37	192 ± 11	426 ± 29	2.81 ± 0.43	3.85 ± 0.44	1.30 ± 0.07

Note: PPO = peak power output; VT_1, VT_2 = first and second ventilatory thresholds; RER peak = peak respiratory exchange ratio.

Table 2 Measured Variables During T_{max} Tests 1 and 2 (*N* = 43)

	T_{max} (s)	$\dot{V}O_2$peak ($L \cdot min^{-1}$)	HR peak (bpm)
Test 1	237 ± 57	4.83 ± 0.46	183 ± 11
Test 2	245 ± 57	4.83 ± 0.46	182 ± 10
r	0.88*	0.90*	0.88*
CV	6 ± 6%	3 ± 2%	2 ± 1%

Note: CV = coefficient of variation: T_{max} = time to exhaustion at $\dot{V}O_2$peak power output. *Significant correlation, $p < 0.001$

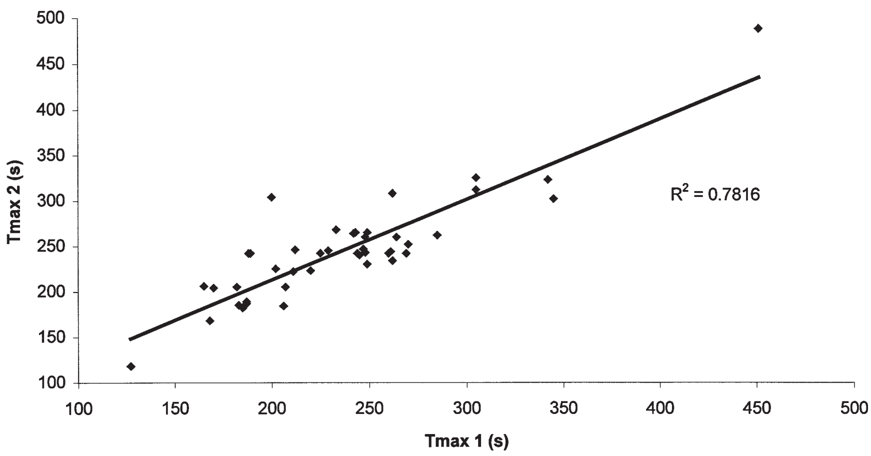

Figure 1. Relationship between the first and second T_{max} tests (*N* = 43).

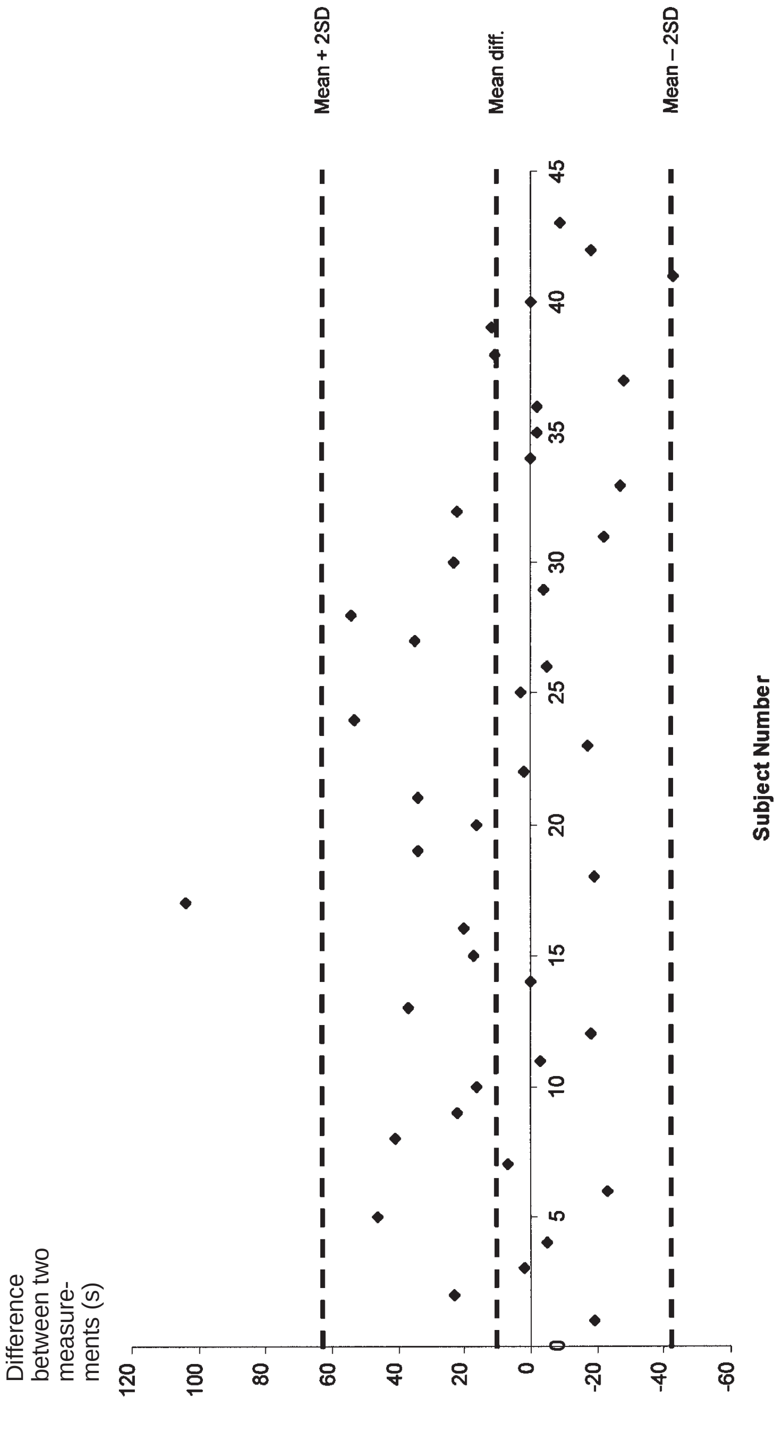

Figure 2. Reproducibility of the time to exhaustion at peak oxygen uptake power output (T_{max}). Bland-Altman plot showing the difference between the first and second T_{max} test against the mean value for each subject ($N = 43$).

Discussion

The main finding in the present study was that the second of two T_{max} measurements in a group of highly trained cyclists was related to ($r = 0.88$; $p < 0.001$), but also significantly greater than, the first ($p = 0.047$). The practical significance of this finding is twofold. First, the assessment of performance ability in cyclists might not be as reproducible as had been previously thought (Billat et al., 1994b). Second, if a high-intensity interval training program is to be prescribed using a T_{max} score (Laursen et al., 2002c), it is possible that the program may be over- or under-calibrated.

The finding of a significant difference in T_{max} is in contrast to the results of Billat et al. (1994b), who previously reported no difference between two T_{max} scores with 8 sub-elite runners. Given the high training history of the subjects in the present study, the significant but small differences in T_{max} (8 s; +3.4%) are probably not due to an acute neuromuscular training adaptation (Lucia et al., 2000a). The small improvement in performance in the second T_{max} test was more likely due to the psychological effect associated with performing "the last test" (Gleser and Vogel, 1971; Hickey et al., 1992). Hickey et al. (1992) have shown that the last of four 1600-kJ time trials in 8 well-trained cyclists were completed in a significantly faster time than the first three. Physiological variables (i.e., HR, respiratory exchange ratio [RER]) in that study were not different between trials, and Hickey et al. (1992) could only attribute the performance difference to psychological factors; the awareness of the trial as being the last task somehow influenced performance time. In the present study, $\dot{V}O_2$, RER, and HR were also not significantly different between trials (Table 2), further pointing to "psychological factors" as a strong possibility for the significantly longer time recorded for the final T_{max} test. However, the possibility of a type I statistical error to explain this finding also cannot be ruled out (Howell, 1997).

The average value of T_{max} in the present study (241 ± 55 s) is less than that which has been reported for highly trained runners (i.e., 283 to 347 s; Billat et al., 1994b; 1999; 2000), but it is similar to that reported by Billat et al. (1996a) for highly trained cyclists (222 ± 91 s). Figures 1 and 2 reveal some differences in T_{max} between the two tests for the majority of subjects when viewing the data between subjects ($p < 0.05$). The absolute difference in T_{max} scores measured in the present study (21 s) is less than that reported by Billat et al. (1994b) in sub-elite runners (44 s), but the relative difference we have shown (8.5%) is similar (10%; Billat et al., 1994b). The coefficient of variation reported by Billat et al. (1994b), at 25%, was also much higher than the 6% found for the present study. This demonstrates the importance of a familiarisation trial prior to the assessment of T_{max} in highly trained athletes (Laursen et al., in press).

While the present study did show a low coefficient of variation for a time-to-exhaustion test (Hopkins et al., 2001), our results suggest that the measurement of T_{max} in a laboratory setting might not be sensitive enough for the prescription and monitoring of training in an individual cyclist (Figure 2). Open-loop tests, in which the task is open ended (i.e., time-to-exhaustion tests), may result in a greater degree of variation compared to closed-loop tests (i.e., time trials), in which the task is more clearly defined (Hopkins et al., 2001; Laursen et al., 2002b). Indeed, subjects in the present study were also examined for a closed-loop 40-km cycle time trial, and the coefficient of variation for this trial was 0.9 ± 1.0% (Laursen et al., in press). Thus, closed-loop tests may be more appropriate for monitoring performance ability with elite cyclists.

There was no significant difference between $\dot{V}O_2$peak measured during the progressive exercise test and that measured during the T_{max} test. This finding is similar to that reported from previous T_{max} research conducted on treadmills with highly trained runners (Billat et al., 1994b; Hill and Rowell, 1997), but is in contrast with the work of LaVoie and Mercer (1987), wherein $\dot{V}O_2$peak was assessed during a cycling T_{max} test in 5 female rowers. Thus our findings suggest $\dot{V}O_2$peak can be assessed using a constant-load T_{max} test in highly trained cyclists.

In contrast to the similar $\dot{V}O_2$peak scores shown during both incremental and constant-load tests in the present study, we found that HR peak achieved during the T_{max} test (182 ± 10) was significantly lower than that obtained during the progressive exercise test (192 ± 11 bpm; $p < 0.001$). This was also found by Lavoie and Mercer (1987) (174 ± 10 vs. 185 ± 8; $p < 0.05$); however, $\dot{V}O_2$peak in this study was also found to be significantly lower (3.12 vs. 3.75 $L \cdot min^{-1}$; $p < 0.05$). While constant-load T_{max} tests in runners have generally shown HR peak values to be similar to those obtained during incremental running (Billat et al., 1995; 1996b; 1998), Billat et al. (1994b) did report a nonsignificant 3-bpm reduction in HR peak during a constant-load T_{max} test compared with incremental treadmill running.

Our findings of a significantly lower HR peak during the T_{max} test compared with the progressive exercise test, despite no significant difference in $\dot{V}O_2$peak, is somewhat difficult to interpret. Jones et al. (1970) have shown that it takes longer for both heart rate and cardiac output to reach steady-state levels with increasing exercise intensity. This is because HR responds more slowly with sympathetic activation, compared with the effect of vagal withdrawal at the onset of exercise (Rowell, 1993).

While $\dot{V}O_2$ and cardiac output are likely to be related during progressive submaximal exercise (Rowell, 1993), differences in $\dot{V}O_2$ and HR at maximal levels could be due in part to temporal aspects of blood volume distribution. Assuming cardiac output (and thus stroke volume) to be maximal during the last minute of both progressive and constant-load tests, it would still be possible for HR to be higher during the progressive exercise test, due potentially to a greater central-to-peripheral blood volume distribution needed for thermoregulation. Indeed, the duration of the progressive exercise test (13.4 ± 1.2 min) was markedly greater than that of the T_{max} tests in the present study (4.0 ± 1.0 min; $p < 0.001$). Moreover, we found a partial relationship between % HR peak obtained during the T_{max} test and the duration of the T_{max} trial ($r = 0.22$; $p < 0.05$), suggesting that the duration of the constant-load T_{max} test may contribute, in part, to the subject's ability to reach HR values near those of HR peak.

Mean T_{max} in the present study was significantly ($p < 0.05$), but not strongly, related to VT_2 ($r = 0.38$) and $\dot{V}O_2$peak ($r = 0.34$). Our finding of a significant relationship between VT_2 and T_{max} has previously been reported for runners (Billat et al., 1994a; 1994b; Hill and Rowell, 1996). Moreover, the relationship between $\dot{V}O_2$peak and T_{max} in the present study is consistent with that found for female rowers when exercise was performed on a cycle ergometer (LaVoie and Mercer, 1987). However, our finding contrasts with that for runners, where Billat et al. (1994c) and James and Doust (2000) reported a negative relationship. Although T_{max} in the present study was not related to either P_{max} or VT_1, this was not unexpected. While subjects with higher P_{max} scores would be expected to have enhanced performance ability (Hawley and Noakes, 1992), the higher P_{max} assigned to these individuals would also tend to reduce time to fatigue. We were not surprised that T_{max} and VT_1 were not related, as we have recently found that VT_1 is more closely related to ultraendurance performance (P. Laursen, work in progress) than to higher intensity exercise such as that recorded during a T_{max} test.

Certainly the relationship between T_{max} and laboratory-measured physiological variables remains unclear. It is possible, however, that some of these inconsistencies may be due to the inherent psychological difficulties of open-loop designed tests. As we have previously mentioned, it appears that open-loop tests like the T_{max} test are more difficult to reproduce because the subject must rely solely on afferent feedback from muscles, coupled with other confounding fatigue factors (Laursen et al., 2002b; Noakes, 2000). Thus this untested "fatigue factor" may help explain some of the equivocal relationships shown between T_{max} and laboratory-measured variables (Laursen and Jenkins, 2002).

In conclusion, the present study has shown that T_{max} scores measured one week apart in highly trained cyclists were significantly different from each other ($p < 0.05$). The present study has also shown that with highly trained cyclists, T_{max} is moderately related to VT_2 and $\dot{V}O_2$peak.

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