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# The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry

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# The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry

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*Keywords*: Critical power; Bicycle ergometry.

The purpose of this study was to determine the relationship between actual time to exhaustion or time limit ($AT_{LIM}$) during bicycle ergometry and predicted time to exhaustion ($PT_{LIM}$) from the Critical Power (CP) test. Fourteen males ($\bar{x} \pm SD = 22{\cdot}36 \pm 2{\cdot}13$ years) volunteered as subjects for this investigation. The subjects visited the laboratory on seven occasions separated by at least 24 h. The first two visits were used for the determination of CP; during the remaining sessions the subjects rode a Monarch bicycle ergometer at power loadings of CP − 20%, CP, CP + 20%, CP + 40% and CP + 60% for the determination of $AT_{LIM}$. Theoretically, power loadings $\leqslant$ CP can be maintained indefinitely without exhaustion and the $PT_{LIM}$ for power loadings > CP can be estimated from the results of the CP test. The accuracy of the CP test for estimating the time to exhasution during bicycle ergometry was determined by comparing $AT_{LIM}$ to $PT_{LIM}$ using correlation coefficients, standard error of estimates and related *t*-tests. The results of this study indicated that there were no significant ($p > 0{\cdot}05$) differences between $AT_{LIM}$ and $PT_{LIM}$ for power loadings > CP ($AT_{LIM}$ vs $PT_{LIM}$ at CP + 20% = $8{\cdot}19 \pm 3{\cdot}90$ vs $7{\cdot}13 \pm 2{\cdot}69$ min, $t = 2{\cdot}106$, $r = 0{\cdot}893$, SEE = 1·21 min; CP + 40% = $3{\cdot}60 \pm 1{\cdot}37$ vs $3{\cdot}46 \pm 1{\cdot}18$ min, $t = 0{\cdot}842$, $r = 0{\cdot}882$, SEE = 0·556 min; CP + 60% = $2{\cdot}36 \pm 0{\cdot}95$ vs $2{\cdot}32 \pm 0{\cdot}79$ min; $t = 0{\cdot}328$ $r = 0{\cdot}841$, SEE = 0·428 min). Power curve analyses however, indicated that the CP test overestimated the power loading which could be maintained for 60 min by a mean of approximately 17%.



## 1. Introduction

Moritani *et al.* (1981) developed a bicycle ergometer analogue of the Critical Power (CP) test proposed by Monod and Scherrer (1965) for synergic muscle groups. The CP test involves a series of exhaustive workbouts at various power loadings from which the total amount of work performed or work limit ($W_{LIM}$) and the time to exhaustion or time limit ($T_{LIM}$) are determined. The $W_{LIM}$ is defined as the product of the imposed power loading ($p$) and the $T_{LIM}$ ($W_{LIM} = p(T_{LIM})$). The relationship between $W_{LIM}$ and $T_{LIM}$ (figure 1) has been shown to be highly linear at $r > 0{\cdot}98$ (Monod and Scherrer 1965, Moritani *et al.* 1981, Bulbulian *et al.* 1986) and can be described by the equation for a straight line: $W_{LIM} = a + b(T_{LIM})$. The slope ($b$) and $y$-intercept ($a$) of the $W_{LIM}$ vs $T_{LIM}$ plot have been termed CP and anaerobic work capacity (AWC) respectively (Moritani *et al.* 1986, Bulbulian *et al.* 1986). It has been suggested that CP represents the maximal power loading which can be maintained without exhaustion and the AWC is the total work capacity associated with the muscular energy reserves and is not dependent upon circulatory oxygen supply (Monod and Scherrer 1965, Moritani *et al.* 1981). As shown in figure 1, CP theoretically corresponds to the asymptote of the relationship between $p$

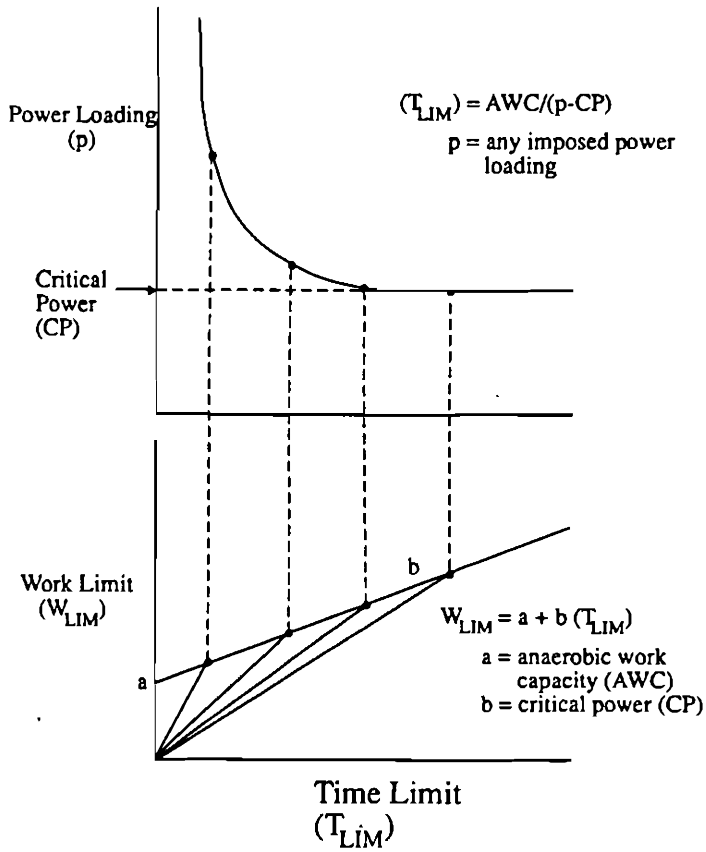


Figure 1. Schematic diagram of the relationships between imposed power loading ($p$) versus time limit ($T_{LIM}$) and work limit ($W_{LIM}$) versus time limit ($T_{LIM}$).



and $T_{LIM}$ which is described by the equation $T_{LIM} = AWC/(p - CP)$. This equation is derived by solving for $T_{LIM}$ using the two equations for $W_{LIM}$:

$$W_{LIM} = p(T_{LIM}) \text{ and } W_{LIM} = a + b(T_{LIM}) \text{ thus, } T_{LIM} = a/(p - b) \qquad (1)$$

where $a = AWC$
$p =$ imposed power loading
$b = CP$

therefore, $T_{LIM} = AWC/(p - CP)$.

Moritani *et al.* (1981) have suggested that this equation can be used to predict the $T_{LIM}$ for any $p > CP$, however when the $p$ is $\leqslant CP$, the work may be continued 'almost indefinitely'.

Previous investigations have examined the validity of CP by comparing it to established threshold parameters. For example, Moritani *et al.* (1981) and de Vries *et al.* (1982) found that CP was highly correlated ($p < 0.01$) with the ventilatory threshold ($r = 0.927$) and the physical working capacity at the fatigue threshold ($r = 0.869$). These findings provide indirect support for the hypothesis that CP represents the maximal power loading which can be maintained without exhaustion. However, the accuracy of the equation $T_{LIM} = AWC/(p - CP)$ and the concurrent validity of CP have not been directly established by having subjects work to exhaustion at various percentages of CP. Therefore the purpose of this investigation was to compare the predicted $T_{LIM}$ ($PT_{LIM}$) using the equation $T_{LIM} = AWC/(p - CP)$ from the CP test to the actual $T_{LIM}$ ($AT_{LIM}$) from work-bouts at power loadings equal to CP − 20%, CP, CP + 20%, CP + 40% and CP + 60%.

## 2. Method

### 2.1. *Subjects*

Fourteen males (Mean ± SD = 22·36 ± 2·13; range = 20–27 years) volunteered as subjects of this investigation. Descriptive characteristics of the subjects are presented in table 1. Informed consent was received from each subject prior to inclusion into the study.

### 2.2. *Procedure*

The subjects visited the laboratory on seven occasions. The first two visits were used for the determination of CP, while the remaining five visits were used to determine the subject's actual time limit at five different power loadings. Each laboratory visit was separated by > 24 h.

### 2.3. *Protocol for the determination of CP*

CP was determined using a slight modification of the technique described by Moritani *et al.* (1981). The subjects performed four dynamic exercise bouts on a Monarch bicycle ergometer. The power loadings for these exercise bouts ranged from 172–360 W depending upon the fitness level of the subject. Rest periods between each exercise bout continued until the subject's heart rate returned to within 10 beats per minute (bpm) of pre-exercise levels (this typically took 30 min or longer). The subjects performed two of the exercise bouts on one day and two on another day with > 24 h between the testing days. Prior to each exercise bout the seat height of the bicycle was adjusted for near full extension of the subject's legs while pedalling. Foot straps were adjusted to prevent the feet from slipping off of the pedals during the testing. The subject warmed up for 4 min by pedalling at a resistance of 34 W. Following a 2-min rest period the subject began pedalling at a rate of 70 revolutions per minute (rpm) against no resistance. The appropriate resistance was set within the first 2–3 s of the test. The subject was encouraged to maintain that pedalling rate throughout the test. Each test was terminated immediately when the subject was unable to maintain 65 rpm as determined by the digital read-out on the Monarch ergometer which had previously been validated against a metronome. This procedure resulted in a very precipitous end to each work-bout thus reducing the effect of changes in the power output as a result of minor fluctuations in the pedalling rate. The subject was allowed to cool down by pedalling

Table 1. Descriptive characteristics of the subjects ($n = 14$).

| Characteristic | $\bar{X} \pm SD$ | Range |
|---|---|---|
| 1. Age (yrs) | 22·36 ± 2·13 | 20–27 |
| 2. Height (cm) | 181·40 ± 6·10 | 171·50–194·50 |
| 3. Weight (kg) | 76·56 ± 13·18 | 62·76–109·20 |
| 4. Critical Power (W) | 197 ± 39 | 138–262 |
| 5. Anaerobic work capacity (J) | 14749 ± 4642 | 6777–23169 |

against no resistance until his heart rate returned to approximately 110 bpm. The $T_{LIM}$ of each test was recorded to the nearest 0·1 s and the $W_{LIM}$ was calculated by multiplying the imposed power loading by the $T_{LIM}$.

### 2.4. *Protocol for the determination of the $AT_{LIM}$*

The results of the CP test allowed for the calculation of a predicted time to exhaustion ($PT_{LIM}$) at any selected power loading using the formula $T_{LIM} = AWC/(p - CP)$. To determine the accuracy of this prediction, the subjects visited the laboratory on five additional days to perform randomly-ordered exercise bouts on the bicycle ergometer at power loadings approximately equal to CP − 20% (156 ± 35 W), CP (191 ± 39 W), CP + 20% (235 ± 46 W), CP + 40% (276 ± 55 W) and CP + 60% (314 ± 60 W) (table 2). The power loadings were administered in a blind fashion so that the subject was unaware of the individual workloads until he had completed all of the exercise bouts. Due to the limited resolution for determining resistance on the Monarch ergometer these power loading represented approximately 79 ± 4, 97 ± 2, 120 ± 2, 140 ± 2 and 160 ± 3% of CP respectively (table 2). The procedures for these exercise bouts were identical to those used for the determination of CP. Following the appropriate adjustment of the seat height and the standardized warm-up, the subjects pedalled at 70 rpm against the predetermined power loading. The test was again terminated when the subject was unable to maintain a 65 rpm cadence. The standardized cool-down period followed each exercise bout. Previous research suggests that power loadings ⩽ CP can be maintained indefinitely (Monod and Scherrer 1965, Moritani *et al.* 1981). Therefore, the workbouts performed at power loadings which were ⩽ CP were terminated at 1 h if the subject had not reached exhaustion.

## 3. Results

### 3.1. *Relationship between $AT_{LIM}$ and $PT_{LIM}$*

Table 2 indicates that there were no significant differences between the $AT_{LIM}$ and $PT_{LIM}$ at power loadings above CP (314 ± 60 W, 276 ± 55 W, and 235 ± 46 W). Simple linear regression indicated that the correlations between $AT_{LIM}$ and $PT_{LIM}$ for power loadings above CP ranged from $r = 0{\cdot}841$ to $r = 0{\cdot}893$ ($p < 0{\cdot}05$) with SEE values ranging from 0·428 to 1·211 minutes. At CP − 20% (156 ± 35 W), 13 of 14 of the subjects were able to complete a 1 h work-bout. The other subject maintained 85% of CP for 27·01 min. At CP (191 ± 39 W) the subjects maintained the power loading for a mean of 33·31 ± 15·37 min (range = 18·42 − 60·00 min).

Table 2. Comparisons between the predicted time to exhaustion ($PT_{LIM}$) and actual time to exhaustion ($AT_{LIM}$) at various power loadings.

| Percent of CP | Power loading (W) | $AT_{LIM}$ (min) | $PT_{LIM}$ (min) | $t$ | $r$ | SEE (min) |
|---|---|---|---|---|---|---|
| 79 ± 4 | 156 ± 35 | 57·64 ± 8·82 | 60·00* | −1·002 | | |
| 97 ± 2 | 191 ± 39 | 33·31 ± 15·37 | 60·00* | −6·494** | | |
| 120 ± 2 | 235 ± 46 | 8·19 ± 3·90 | 7·13 ± 2·69 | 2·106 | 0·893** | 1·211 |
| 140 ± 2 | 276 ± 55 | 3·60 ± 1·37 | 3·46 ± 1·18 | 0·842 | 0·882** | 0·556 |
| 160 ± 3 | 314 ± 60 | 2·36 ± 0·95 | 2·32 ± 0·79 | 0·328 | 0·841** | 0·428 |

* Theoretically power loadings ⩽ CP could be maintained indefinitely without exhaustion, however the work-bouts were terminated at 60·00 min if fatigue had not occurred.
** $p < 0{\cdot}05$.

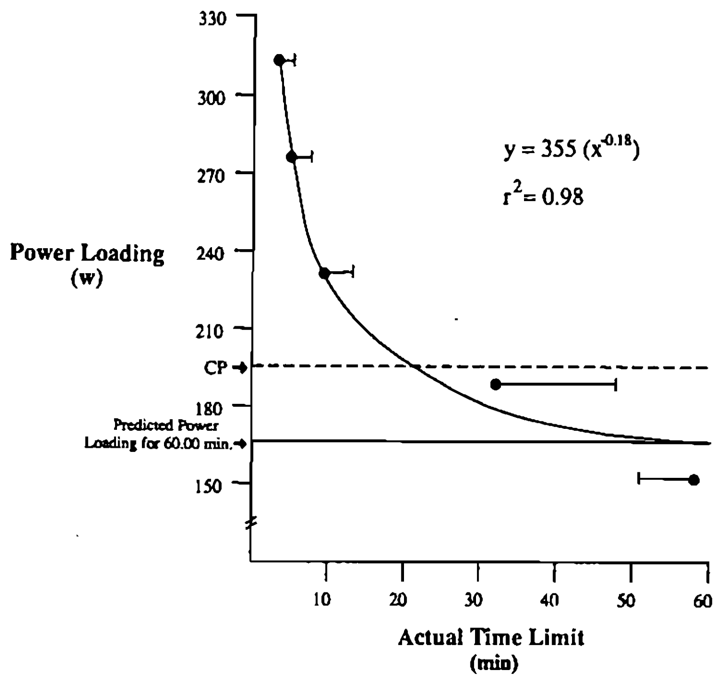


Figure 2. The relationship between the mean values for the imposed power loadings and actual time limit.

To estimate the maximal power loading which could be maintained for 60 min, a power curve ($ax^b$) was derived from the hyperbolic relationship between the power loadings and $AT_{LIM}$ for each subject (figure 2). The correlations for the power curves ranged from $r = 0.84$ to $1.00$ and all were significant at $p < 0.05$. Theoretically it should have been possible for the subjects to maintain CP indefinitely, therefore the estimated power loadings which could be maintained for 1 h were compared to the CP values using a related *t*-test. The results indicated that the true CP ($197 \pm 39$ W) was significantly ($p < 0.05$) greater than the estimated value ($164 \pm 32$ W) which corresponded to 83% of CP. They were, however, highly correlated ($r = 0.912$, SEE = 12 W).

## 4. Discussion

The non-significant mean differences and high correlations between $AT_{LIM}$ and $PT_{LIM}$ in the present investigation support the findings of Moritani *et al.* (1981) which indicated that the time to exhaustion for power loadings > CP could be calculated using the equation: $T_{LIM} = AWC/(p - CP)$. The physiological mechanism responsible for muscular fatigue at these power loadings however, is unclear. Moritani *et al.* (1981) suggested that at power loadings > CP, the muscle must utilize its energy reserves including intra-muscular phosphogens, glycogen and oxygen stores and fatigue will occur when these reserves are depleted. This hypothesis was proposed to explain the premise of the equation $T_{LIM} = AWC/p - CP$ which indicates that the work capacity associated with stored energy sources within the muscle (AWC) will be utilized at a predictable rate based on the magnitude of the difference between the imposed power loading ($p$) and CP. However, the underlying assumption of this hypothesis may not be true. For example, it has been shown that exhaustive exercise bouts on a bicycle ergometer at 90 or 120% of $\dot{V}O_2$ max and lasting < 30 min resulted in approximately a 30% depletion in muscle glycogen stores (Saltin and Karlsson 1971). These findings suggest that at high power loadings, such as those above CP, energy substrate availability in the form of muscle glycogen does not limit exercise endurance. It is possible that muscular fatigue at power loadings > CP results from lactic acid accumulation or creatine phosphate depletion.

Theoretically, CP is analogous to the concept of lactate threshold (LT) in that both parameters provide a method for identifying the maximal power loading that can be maintained for an extended period of time without exhaustion and above which fatigue will limit endurance performance. The LT normally occurs at 50–80% of $\dot{V}O_2$ max which corresponds to a blood lactate level of approximately 2 mM (Ivy *et al.* 1980, Kumagai *et al.* 1982, Green *et al.* 1983, Ribeiro *et al.* 1986) and previous investigations (Costill 1970, Farrell *et al.* 1979, Tanaka and Matsuura 1984) have shown that exercise at this intensity could be continued for > 2 h. In addition, Ribeiro *et al.* (1986) and Stegmann and Kindermann (1982) have shown that cycle ergometry can be maintained for at least 40 to 50 min at blood lactate levels of 4 to 5 mM. The subjects in the present study however, were able to maintain CP for a mean of only 33·31 ± 15·37 min (range = 18·42 – 60·00 min) with 11 of 14 subjects failing to complete a 1 h work-bout. Furthermore, the power curve analyses indicated that CP overestimated the exercise intensity which could be maintained for 60 min by a mean of approximately 17%. Therefore it is likely that CP corresponds to a power loading substantially above LT.

## 5. Conclusions

The results of this investigation indicated that the equation $T_{LIM} = AWC/p - CP$ from the CP test provided an accurate estimate of the subjects' muscular working capacities at power loadings > CP. However, it appears that muscular fatigue at power loadings > CP is not a function of the depletion of energy reserves, as hypothesized by Moritani *et al.* (1981). In addition, it is likely that CP is above LT and the present findings indicated that CP was approximately 17% greater than the power loading which could be maintained for 60 min.

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L'objectif de cette étude était de déterminer la relation entre le temps réel jusqu'à épuisement out temps limite ($AT_{LIM}$) pendant un exercice sur ergocycle et le temps prédit pour l'épuisement ($PT_{LIM}$) à partir du test de puissance critique (CP). Quatorze sujets ($X \pm$ E.T. = 22,36 ± 2,13 ans) ont participé à l'expérience. Les sujets sont venus au laboratoire à sept moments différents séparés apr, au moins, 24 heures. Les deux premiers passages ont servi à la détermination de la CP. Au cours des autres, ils ont pédalé sur un ergocycle type Monarch avec des charges de CP-20%, CP, CP+20%, CP+40% et CP+60%, pour la détermination de $AT_{LIM}$. Théoriquement, des puissances ≤ CP peuvent être maintenues indéfiniment sans épuisement et la $PT_{LIM}$ pour les puissances > CP peuvent être estimées à partir des résultats au test CP. La précision du test CP pour estimer le temps jusqu'à épuisement pendant l'ergomètrie sur bicycle a été déterminée en comparant $AT_{LIM}$ à $PT_{LIM}$ au moyen des coefficients de corrélation, l'erreur-type sur les estimations et les tests t de Student. Les résultats de cette étude montrent qu'il n'y a pas de différences significatives ($p > 0{,}05$) entre $AT_{LIM}$ et $PT_{LIM}$ pour des puissances > CP ($AT_{LIM}$ vs. $PT_{LIM}$ à CP + 20% = 8,19 ± 3,9 vs. 7,13 ± 2,69 mn; $t = 2{,}106$; $r = 0{\cdot}893$; E.T.E. = 1,21 mn. CP + 40% = 3,60 ± 1,37 vs. 3,46 ± 1,18 mn; t = 0,842; r = 0,882; E.T.E. = 0,556 mn. CP + 60% = 2,36 ± 0,95 vs. 2,32 ± 0,79 mn; $t = 0{,}328$; $r = 0{,}841$; E.T.E. = 0,428 mn). Les analyses de la courbe de puissance montrent cependant que le test CP sur-estime d'environ 17% la puissance qui peut être maintenue pendant 60 mn.

Ziel dieser Studie war die Bestimmung der Beziehung zwischen tatsächlicher Zeit bis zur Erschöpfung bzw. der Maximalzeit ($AT_{LIM}$) während der Arbeit am Fahrradergometer-und der vorhergesagten Zeit bis zur Erschöpfung ($PT_{LIM}$) aus dem Dauerleistungstest (Critical Power Test = CT). Vierzehn Männer ($X \pm$ SD = 22,36 ± 2,13 Jahre) stellten sich freiwillig als Versuchspersonen für diese Untersuchung zur Verfügung. Die Versuchspersonen kamen an sieben Terminen in das Labor, zwischen denen mindestens 24 h lagen. Die ersten beiden Termine wurden zur Bestimmung des CP genutzt, während der übrigen Versuche fuhren die Versuchspersonen auf eimen Monarch-Fahrradergometer mit Leistungen von CP − 20%, CP, CP + 20%, CP + 40% und CP + 60% zur Bestimmung von $AT_{LIM}$. Theoretisch können Leistungen ≤ CP unbegrenzt und ohne Erschöpfung aufrecht erhalten werden, und die $PT_{LIM}$ für Leistungen > PT kann aus den Ergebnissen des CP-Tests geschlossen werden. Die Genauigkeit des CP-Tests zur Abschätzung der Zeit bis aur Erschöpfung während der Arbeit am Fahrradergometer wurde durch den Vergleich von $AT_{LIM}$ mit $PT_{LIM}$ überprüft. Dazu wurden

Korrelationskoeffizienten, Standardfehler der Schätzung (SEE) und verwandte $T$-Tests eingesetzt. Die Ergebnisse dieser Studie zeigten, daß keine signifikanten ($p > 0{,}05$) Unterschiede zwischen $AT_{LIM}$ und $PT_{LIM}$ für Leistungen > CP bestanden ($AT_{LIM}$ vs $PT_{LIM}$ bei CP + 20% = 8,19 ± 3,90 vs 7,13 ± 2,69 min, $t = 2{,}106$, $r = 0{,}893$, SEE = 1,21 min; CP + 40% = 3,60 ± 1,37 vs 3,46 ± 1,18 min, $t = 0{,}842$, $r = 0{,}882$, SEE = 0,556 min; CP + 60% = 2,36 ± 0,95 vs 2,32 ± 0,79 min, $t = 0{,}328$, $r = 0{,}841$, SEE = 0,428 min). Die Analysen der Leistungsverläufe zeigten jedoch, daß der CP-Test die Leistung, die über eine Zeit von 60 min aufrecht erhalten werden kann, im Mittel um 17% überschätzt.

本研究の目的は自転車エルゴメトリイ中の実際の疲労困憊時間すなわち時間限度（$AT_{LIM}$）と臨界パワー（CP）試験から予測した疲労困憊時間の関係を求めることであった。14名の男性（x ± SD = 22.36 ± 2.13歳）が本研究に被験者として志願した。被験者は少なくとも24時間の間をおいて７回実験室を訪れた。最初の二回はCPの測定に充てられた。残りの回で被験者はCP − 20%，CP，CP + 20%，CP + 40%およびCP + 60%のパワー負担でMonarch自転車エルゴメータに乗り$AT_{LIM}$を測定した。理論的には，パワー負担＜CPは疲労困憊なしに無限に維持できるし，パワー負担＞CPでの$PT_{LIM}$はCP試験の結果から推定できる。自転車エルゴメトリイ中の疲労困憊時間を推定するCP試験の精度は相関係数，標準推定誤差，関連t検定を使用して，$AT_{LIM}$と$PT_{LIM}$を比較して求めた。本研究結果によると，パワー負担＞CPの場合，$AT_{LIM}$と$PT_{LIM}$の間には有意差はなかった（$AT_{LIM}$ vs $PT_{LIM}$ at CP + 20% = 8.19 ± 3.90 vs 7.13 ± 2.69min，t = 2.106，r = 0.893，SEE = 1.21min；CP + 40% = 3.60 ± 1.37 vs 3.46 ± 1.18min；t = 0.842，r = 0.882，SEE = 0.556min；CP + 60% = 2.36 ± 0.95 vs 2.32 ± ..79min；t = 0.328，r = 0.841，SEE = 0.428min)。パワー曲線分析によると，しかし，CP試験は60分間維持できるパワー負担を平均して約17%過大評価していた。