Validity of Dynamic Prediction Model for Oxygen Uptake during Supra Maximal Intermittent Load Exercise

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The purpose of this study was to determine the validity of a dynamic prediction (DP) model that predicts oxygen uptake ($\dot{V}O_2$) during supra maximal intermittent (SMI) exercise based on non-linearity of $\dot{V}O_2$ dynamics in comparing a heart rate (HR) model. Five male participants (20 ± 1 yrs) performed incremental exercise test used by cycle ergometer for the aim of developing individualized HR- $\dot{V}O_2$ and workload- $\dot{V}O_2$ regression equations. The DP model was defined as a first order system to workload- $\dot{V}O_2$ relationship. Participants then completed SMI test corresponding at 140 % $\dot{V}O_{2max}$ while HR and $\dot{V}O_2$ data were collected continuously for 20 min. The HR model predicted $\dot{V}O_2$ during SMI test used by HR, while the DP model also predicted $\dot{V}O_2$ from workload. Predicted values ($\dot{V}O_2$) were compared with measured values ($\dot{V}O_2$) obtained via a metabolic measurement system. The DP model showed a significantly higher relationship with measured $\dot{V}O_2$ ($R^2 = 0.95$, SEE = 149 ml/min) in comparison with the HR model ($R^2 = 0.83$, SEE = 275 ml/min). The HR model showed significant systematic error ($r = 0.41$, $P < .05$), whereas the DP model did not ($r = 0.06$, $P > .05$). For comparison of prediction errors of both models, the error of the DP model (-1.3 ± 8.8 %) was significantly smaller than the HR model (-8.0 ± 16.5 %). The DP model also accurately estimated total energy expenditure. Therefore, the DP model is an accurate predictor of $\dot{V}O_2$ during supra maximal intermittent exercise.

Keywords: exercise intensity, heart rate, validity, accuracy

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1. Introduction

In exercise training, intensity has been expressed in oxygen uptake ($\dot{V}O_2$), relative value to maximum oxygen uptake ($\% \dot{V}O_{2max}$) and metabolic equivalents (METs) (American College of Sports Medicine: ACSM, 2000). There are many studies which have reported scientific evidence that the improvement of exercise performance depends on intensity (Busso, et al., 1990; Morton, et al., 1990; Pate & Branch, 1992; ACSM, 2000). Therefore, it is necessary to monitor intensity in order to verify how effectively training is being carried out.

As a method for monitoring intensity, heart rate (HR) monitoring is widely used to predict $\dot{V}O_2$ during exercise (Morton, et al., 1990; O'Toole, et al., 1998; ACSM, 2000; Strath, et al., 2002). In the HR monitoring method, a $\dot{V}O_2$ prediction equation (HR model) is individually developed by linear regression analysis, setting HR during incremental load exercise as the independent variable and $\dot{V}O_2$ as the dependent variable. The procedure for preparing the HR model is a relatively easy and useful method for monitoring exercises ranging from low to high intensity. There are, however, some problems.

In the HR model, it is presupposed that the

relationship between HR and $\dot{V}O_2$ during exercises is always linear. Nevertheless, since the linear relationship between HR and $\dot{V}O_2$ cannot be established during intermittent exercises that accompany sudden load changes and during exercises exceeding the $\dot{V}O_{2\max}$ intensity (supra maximal intensity) (Achten, 2003), the HR model is markedly deteriorated in prediction accuracy during supra-maximum intermittent exercises. Deterioration of prediction accuracy might be caused by difference between $\dot{V}O_2$ dynamics and HR dynamics to the workload (Bearden & Moffatt, 2001; Hughson, 2003). Both HR and $\dot{V}O_2$ dynamics during constant load exercises have been described by the exponential function model (Bearden & Moffatt, 2001). It has been reported that the time constant estimated from the model is a parameter which presents the response speed to the workload and that the time constant between HR and $\dot{V}O_2$ dynamics is significantly different (Bearden & Moffatt, 2001; Hughson, 2003).

Recently, many studies have adopted $\dot{V}O_2$ dynamics modeling, and its characteristics to the workload have been explained (Pool, et al., 1994; Morton & Gregory, 1987; Miyamoto & Niizeki, 1990; Hughson, et al., 1991; Swanson & Hughson, 1988; Bell, et al., 1999; Cabrera, et al., 1999; Bahr, et al., 1992; Perrey, et al., 2002). Because the dose-response relationship between workload and $\dot{V}O_2$ dynamics is better defined, in the prediction of intensity under the conditions in which the workload (watt and running velocity) is easily obtained, such as with a bicycle ergometer or tread ergometer, it is preferable to get $\dot{V}O_2$ dynamics directly as the prediction method. The present study examined the validity of a $\dot{V}O_2$ dynamic prediction (DP) model based on $\dot{V}O_2$ dynamics characteristics in supra-maximum intermittent exercises by comparing it with the HR model.

2. Methods

2.1. Subjects

Five healthy males participated in this study. Their mean $\pm$ SD of age, height, and weight were 20.0 $\pm$ 1.0 years, 176.6 $\pm$ 5.4 cm, and 73.1 $\pm$ 5.5 kg, respectively. After a detailed explanation of the study, informed

consent was obtained.

2.2. Workload test

All tests were carried out in a laboratory controlled at a room temperature of 25°C and humidity of 50%. Using an electrically braked cycle ergometer (aerobike 75XLII, Combi Co., Tokyo, Japan), for all tests, the subjects conducted a 3 min warm-up (0 W) after a 5 min rest. The pedal frequency was held constant at 60 rpm during all tests. In the multi-stage incremental load test, after a warm-up, the workload was increased by 30 W/3 min after warming up and they performed to exhaustion. In the supra-maximum intermittent (SMI) test, one set consisted of a low load (60 W, 30.3 $\pm$ 1.8% $\dot{V}O_{2\max}$: Base) for the starting 3 min, and a heavy intensity load (Trial) corresponding to 140% $\dot{V}O_{2\max}$ for the subsequent 1 min, and the subjects had to repeat 5 sets. All the subjects performed the multi-stage incremental load test on the first day and the SMI test on another day. Multi-stage incremental load test data were used for modeling of the HR model and the DP model, and SMI test data were set as the validity criterion.

$\dot{V}O_2$ and HR in all tests were measured from rest to the end of exercise by a breath-by-breath method using AE-300s (Minato Medical Science Co., Osaka, Japan). The measured values of $\dot{V}O_2$ and HR were averaged for 60 sec intervals both in the multi-stage incremental load test and the SMI test.

$\dot{V}O_{2\max}$ was determined from multi-stage incremental load test data. $\dot{V}O_{2\max}$ was decided with leveling-off when an increase of $\dot{V}O_2$ becomes below 150 ml/min of the previous load, as the first

Figure 1 Super maximal intermittent (SMI) test protocol.

criterion (Taylor, et al., 1955). When leveling-off was not observed, it was decided at highest $\dot{V}O_2$ at the time of appearance of R of above 1.15 (Tanaka, et al., 1986).

2.3. DP model

Feedback control works in many physiological responses. Feedback control is considered to work on the energy supply system during exercise, too. That is, deficiency of energy at an early period of exercise and recovery period increases or decreases energy supplement. With the decrease in the difference between supply and demand, the increase or decrease of the energy supply system becomes moderate and, then, reaches a steady state. The $\dot{V}O_2$ steady state is proportional to the workload (Medbø, et al., 1988). This relationship explains why the main dynamics of $\dot{V}O_2$ are regarded as the first order system to the workload or energy demand (Pool, et al., 1996; Morton & Gregory, 1987; Miyamoto & Niizeki, 1990; Hughson, et al., 1987). Accordingly, the DP model was described as the following:

$$\dot{V}O_2(t) = \dot{V}O_2(t - dt) + \Delta \dot{V}O_2 \cdot dt$$

$$\Delta \dot{V}O_2 = \dot{V}O_2 \text{ discrepancy} / \tau$$

$$\dot{V}O_2 \text{ discrepancy} = \text{MIN}((\text{Energy} - \dot{V}O_2), (\dot{V}O_{2\text{max}} - \dot{V}O_2))$$

$$\text{energy demand} = a \cdot \text{Work rate} + b$$

where, a = regression coefficient; b = regression constant, τ = time constant 30 sec; MIN = minimal function. Regression analysis was used for the estimation of regression coefficient and regression constant, and the time constant τ was determined from previous studies (Hughson, et al., 1991; Swanson & Hughson, 1988; Bell, et al., 1999; Cabrera, et al., 1999). The MIN function selects a minimal argument out of the arguments in parentheses. Even if energy demand is more than $\dot{V}O_{2\text{max}}$, $\dot{V}O_2$ does not exceed $\dot{V}O_{2\text{max}}$. Energy demand was determined by the linear regression expression with the last 1 min $\dot{V}O_2$ being the dependent variable, and the workload being the independent variable at each load stage in the multi-stage incremental load test. The hypothesis that $\dot{V}O_2$ dynamics reaches a steady state in 3 min considers the characteristic of reaching a steady state in the time passage 4 times the time constant

(30 sec) when regarding $\dot{V}O_2$ dynamics as the first order system to the workload (Furuta, et al., 2001). The criterion to accept a regression line was the determination coefficient of more than $R^2 = 0.98$.

In the post-exercise recovery period more than the intensity of 70% $\dot{V}O_{2\text{max}}$, effects of post-exercise excess oxygen consumption (EPOC) were observed (Schneider, et al., 1968; Bahr, et al., 1992), and the time constant of $\dot{V}O_2$ dynamics changes (Perrey, et al., 2002). Perrey, et al. (2002) have reported that by the effect of EPOC, the time constant τ becomes slower to approximately 95 sec. Therefore, EPOC effects in the DP model were described using the IF function as follows:

$$\Delta \dot{V}O_2 = \text{IF}((\text{SMTH1}(\text{work rate}, 60 \text{ sec}) \geq \text{work rate at } 70\%\dot{V}O_{2\text{max}}) \text{ and } > \dot{V}O_2 \text{ discrepancy} < 0)$$

$$\text{THEN } (\dot{V}O_2 \text{ discrepancy}/95 \text{ sec})$$

$$\text{ELSE } (\dot{V}O_2 \text{ discrepancy}/30 \text{ sec})$$

where, SMTH1 is a smoothing function. When the workload 60 sec before had an average of more than the workload in the 70% $\dot{V}O_{2\text{max}}$ level and the $\dot{V}O_2$ discrepancy was negative, we set the time constant of $\dot{V}O_2$ dynamics to 95 sec and to 30 sec for other conditions.

The DP model was modeled using the software STELLA 5.1J (High Performance, New Hampshire, USA) specially designed for System Dynamics that is a technique of dynamic simulation. The fourth-order Runge-Kutta method was used to compute the model, and the delta time of computation was 20 sec.

2.4. HR model

The HR model was modeled by applying a method (flex heart rate: Flex HR) established by Livingstone, et al. (1990). Flex HR is a method that solves underestimation of $\dot{V}O_2$ during low intensity exercises. This solution method against $\dot{V}O_2$ underestimation substitutes the average of highest HR during rest and lowest HR during the multi-stage incremental load test (Flex HR point) when an HR lower than the HR during rest was obtained in the multi-stage incremental load test. The HR model was determined by the regression line with the HR obtained from the incremental load test being the independent variable and $\dot{V}O_2$ the dependent variable. As the criterion to accept the individual HR

Table 1 Comparison of relative error scores (RES) between HR and DP models.

Subjects	Age	Height	Weight	VO ₂ max	HRmax	Watt	energy demand			HR model		Workload at SMI test
							slope	constant	R ²	slope	constant	
YS	19	176	72.6	2883	189	240	10.6	593	0.99	21.7	-946	340
TT	19	173	66.4	3101	180	270	10.2	703	1.00	22.7	-1077	380
KT	21	186	77.3	3359	176	270	10.9	673	0.99	23.7	-1084	380
SN	20	174	69.5	3064	186	240	10.7	667	0.99	22.3	-1342	340
KO	21	174	79.7	3093	184	270	9.8	754	0.99	17.8	-756	380
mean	20	177	73.1	3100	183	258	10.4	678		21.6	-1041	364
SD	1	5	5.5	170	5	16	0.4	59		2.3	214	22

Figure 2 Fitting of predictions to measurement during SMI test at 140% $\dot{V}O_{2max}$. Solid line showed measured $\dot{V}O_2$, ● was symbol of predicted values by HR model, ○ was symbol of predicted values by DP model. Theses data were average of all subjects.

models, the determination coefficient of more than $R^2 = 0.98$ was used.

2.5. Statistical analysis

The validity of the HR model and the DP model was examined from determination coefficient to validity criterion (measured $\dot{V}O_2$ obtained from the SMI test), degree of agreement of the models with validity criterion and existence of systematic error in the Bland and Altman plot (1986), comparison of total energy expenditure (TEE), and relative error score (RES) in the total SMI test. The TEE and RES were calculated in the following expression:
 $TEE (kcal) = \text{sum of } \dot{V}O_2 / 1000 (L) \times 5.0 (kcal/O_2 L)$
 $RES (\%) = (\text{prediction} - \text{criterion}) / \text{criterion} \times 100$

For TEE comparison, when a significant main effect could be obtained using ANOVA with repeated measurements (3 levels: validity criterion, the HR model, and the DP model), a multiple comparison test by the Bonfferroni method was performed. For

Table 2 Oxygen uptake (mean±SD) and determination coefficients of HR and DP models to measured $\dot{V}O_2$ during SMI test.

Method	VO ₂ (ml/min)	R ²	ΔEE (ml/min)
Measurment	1807 ± 658	-	-
HR model	1892 ± 547	0.83*	275
DP model	1826 ± 650	0.95*	149

*: $P < .05$

RES comparison, a paired t test was used. The overall significance level was set at $\alpha=0$. All statistical analyses were completed using SPSS 12.0J for Windows.

3. Results

All measured values are shown in the mean±SD. **Table 1** shows the measuring items, energy demand and the HR model of each subject in the multi-stage incremental load test. $\dot{V}O_{2max}$ was 3100 ± 170 ml/min, and the HR maximum value (HRmax) was 183 ± 5 bpm. The regression coefficient of energy demand in the 5 subjects was 10.4 ± 0.4 , and the regression constant was 364 ± 41 . The regression coefficient and constant of the HR model were 21.6 ± 2.3 and -1041 ± 214 . Both energy demand and the HR model showed a determination coefficient ($R^2 \geq 0.98$) of more than the accepted criterion.

Figure 2 shows the goodness of fit of the measured $\dot{V}O_2$, the predicted $\dot{V}O_2$ of the HR model and the DP model in the SMI test. **Table 2** shows the measured $\dot{V}O_2$, the predicted $\dot{V}O_2$ by the HR model, the predicted $\dot{V}O_2$ by the DP model, and the determination coefficient of the HR model and the DP model to the measured $\dot{V}O_2$ during the SMI test. The measured $\dot{V}O_2$ was 1807 ± 658 ml/min, the prediction value by the HR model was 1892 ± 547 ml/min, and the prediction value of the DP model was $1826 \pm$

Figure 3 Bland and Altman plots depicting error scores minute-by-minute prediction for (A) HR model, (B) DP model during SMI test. The solid line represents the mean error, and the dash line represents the 95% confidence interval.

Table 3 Comparison of total energy expenditure predicted by HR and DP models.

Methods	TEE (kcal)
Measurement	180.7 ± 14.2
HR model	189.2 ± 15.0
DP model	182.6 ± 14.4

The main effect was not significant for ANOVA with repeated measurements.

Table 4 Comparison of relative error scores (RES) between HR and DP models.

Methods	RES (%)
HR model	-8.0 ± 16.5*
DP model	-1.3 ± 8.8

*: $P < .05$

650 ml/min. The determination coefficient of the HR model was $R^2 = 0.83$, and that of the DP model was $R^2 = 0.95$.

Figure 3 shows the Bland and Altman plot of the HR model and the DP model in the SMI test. The mean error of the HR model was -86 ml/min and the 95% confidence interval (CI) ranged from 470 to -641 ml/min. The mean error of the DP model was -19 ml/min and 95% CI from 278 to -317. Also, in the Bland and Altman plot, a significant correlation coefficient ($r = 0.41$, $P < .05$) was observed in the error of the HR model.

Table 3 shows the TEE measured in the total SMI test, the predicted TEE by the HR model, and the predicted TEE by the DP model. The measured TEE was 180.7 ± 14.2 kcal, the predicted TEE by the HR model was 189.2 ± 15.0 kcal, and predicted TEE by the DP model was 182.6 ± 14.4 kcal. In ANOVA with repeated measurements, a significant main effect was not observed among 3 levels.

Table 4 shows the RES of the HR model and the DP model. The RES of the HR model was $-8.0 \pm 16.5\%$ while that of the DP model was $-1.3 \pm 8.8\%$.

The RES of the HR model showed a significantly low value in the paired t test.

4. Discussion

The major finding of the present study was that the determination coefficient ($R^2 = 0.95$) to the measured $\dot{V}O_2$ of the DP model showed higher values than the HR model ($R^2 = 0.83$) during supra maximal intermittent exercises. In the Bland and Altman plot, 95%CI of the DP model was in a narrower range than the HR model and there was no systematic error. Also, in RES comparison, the DP model had far fewer errors than the HR model. These results showed that the DP model that considers $\dot{V}O_2$ dynamic characteristics has higher prediction accuracy than the HR model that has been widely used. It can be decide that the DP model is a sufficiently valid method as a $\dot{V}O_2$ prediction method.

The HR model had a systematic error in the Bland and Altman plot ($r = 0.41$, $P < .05$). When visually analyzing the plot, it is assumed that errors in the HR model consist of two components. We

can consider that errors when $\dot{V}O_2$ is less than 1500 ml/min increase toward the negative direction with the increase of intensity and errors more than 1500 ml/min increase toward the positive direction with the increase of intensity (**Figure 3**). Achten (2003) has reported that in the phase of a sudden increase or decrease in the workload, because the HR dynamics becomes slower than the $\dot{V}O_2$ dynamics, the prediction accuracy of $\dot{V}O_2$ of the HR model drastically declines. In the HR model, $\dot{V}O_2$ is underestimated in the phase of a sudden increase of the load and overestimated in the phase of a decrease of the load. In the present study, since supra maximum intermittent exercises set as a valid criterion are exercises that repeat sudden load increase and decrease, two error components visually recognized in the Bland and Altman plot should be a clearly striking result that reflected HR model characteristics. Also, although the HR model showed lower prediction accuracy than the DP model in determination of the coefficient and RES comparison, TEE comparison was not significantly different from the measured TEE. This result might stem from a counterbalance of two error components by the summation of $\dot{V}O_2$.

The DP model examined in the present study had high validity in the supra maximum intermittent pedaling exercise. The DP model is modeled under several hypothetical conditions. Procedures necessary for modeling are collection of incremental load test data and determination of energy demand. Therefore, it should be similar in ease to the modeling of the HR model. Takahashi, et al. (2003) have reported that by modeling an expired gas dynamics model using System Dynamics similar to the DP model, the expired gas dynamics model had sufficient prediction accuracy in $\dot{V}O_2$ prediction at the times of incremental load pedaling exercise and constant load pedaling exercise of sub-maximal intensity (50-70% $\dot{V}O_{2max}$). Accordingly, the DP model is thought to be useful as a $\dot{V}O_2$ prediction method in both steady state and non-steady state. Nevertheless, the validity of the DP model reported in the previous and present studies is limited to pedaling exercises on bicycle ergometers. Pedaling exercise is an easy exercise form for measuring the workload (watt) that is an independent variable of the DP model, so the DP model cannot

satisfy enough applicability. For future research, the applicability of the DP model should be verified as a method to measure running or physical activity in free-living activity (METs) by setting values measured by a pedometer or accelerometer as the independent variable.

In the present study, by the comparison with the HR model, the validity of the DP model in supra maximum intermittent exercise was examined. The DP model showed higher prediction accuracy than the HR model in the measured $\dot{V}O_2$, and the validity of the DP model was verified.

5. Limitations

In this study, to compare the HR model with the DP model, two models were modeled from the same test data, that is, multi-stage incremental load test data. The constructed DP model has the following limitations:

1) Effect of slow component: It is known that there are slow components in $\dot{V}O_2$ dynamics of high intensity exercises over the intensity of lactate threshold (LT) so that systematic errors are contained in the prediction value of the DP model in which the simple first order system to energy demand is presupposed. Since it is difficult to estimate parameters in slow components in the multi-stage incremental load test, future research should be focused on constant load testing of high intensity and to improve the accuracy of the DP model by adding slow component parameters.

2) Individual variation in time constant τ of $\dot{V}O_2$ dynamics: Because it was difficult to estimate the time constant τ when determining dynamic characteristics of $\dot{V}O_2$ dynamics from multi-stage incremental load test data, the present study set the time constant to 30 sec or 95 sec in 70% $\dot{V}O_{2max}$ intensity post-exercise for all the subjects. However, individual variation of approximately ± 20 sec is known according to gender, age, muscular fiber composition and exercise habit in the time constant τ (Morton & Gregory, 1987; Barstow, et al., 1996; Perrey, et al., 2002). For applying the DP model to females, children, middle-aged and elderly people, individual estimation should be prepared for the time constant τ of $\dot{V}O_2$ dynamics.

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Main Works:

- System dynamics modeling of expired gas dynamics during incremental test. *Japan J. Phys. Educ. Hlth. Sport Sci.* 48: 169-180, 2003. (in Japanese with English abstract)
- Validity of expired gas simulation model during constant load exercise. *IJSHS.* 1: 119-128, 2003

Membership in Learned Societies:

- Japan Society of Physical Education, Health and Sport Science
- Japan Society of Physical Fitness and Sports Medicine
- American College of Sports Medicine
- The Japanese Chapter of the System Dynamics Society