Variable Dose-Response Relationship between Exercise Training and Performance

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ABSTRACT

BUSSO, T. Variable Dose-Response Relationship between Exercise Training and Performance. *Med. Sci. Sports Exerc.*, Vol. 35, No. 7, pp. 1188–1195, 2003. **Introduction**: The aim of this study was to propose a nonlinear model of the effects of training on performance. The new formulation introduced a variable to account for training-related changes in the magnitude and duration of exercise-induced fatigue. **Methods:** Goodness-of-fit of the proposed model was compared with that of earlier models presented in the literature. Models were applied to six previously untrained subjects volunteers over a 15-wk endurance-training program composed of an 8-wk period with three sessions per week and a 4-wk period with five sessions, and the remaining weeks without training. Training sessions were composed of performance trial and intermittent exercise with 5-min work interspersed with 3-min recovery repeated four or five times. Performance was measured three times each week using average power during a 5-min all-out exercise. **Results:** The training program resulted in 30 ± 7% improvement in performance. The proposed model exhibited significantly improved fit with actual performance obtained in each subject. Standard error was 6.47 ± 0.71 W for the proposed model and from 9.20 ± 2.27 W to 10.31 ± 1.56 W for earlier models. The model output using model parameters averaged over the six subjects was found to be similar to data published elsewhere obtained in athletes with more intense training. **Conclusion:** The data obtained allowed us to demonstrate an inverted-U-shape relationship between daily amounts of training and performance. The fit between experimental data and model-derived predictions in similar situations showed the usefulness of the proposed model to predict responses to training with varied regimens. **Key Words:** MATHEMATICAL MODEL, FATIGUE, ADAPTATION, TAPER, OVERTRAINING

The relationship between the amount of work performed and the improvement in physical performance achieved appears to be more complex than a simple dose-response effect. Too much training with insufficient recovery between sessions could provide a level of performance lower than expected. Little data are available to examine the quantitative relationship between training and performance. In 1975, Banister and coauthors (1) proposed systems modeling to quantify the relationship. In their model, variations in performance over time were related to training doses, quantified from exercise intensity and duration. The systems model was able to differentiate between the influence of fatigue and adaptation on performance. Model derivations yielded a better understanding of the particular features of tapering and overtraining (12,22,23,26). A study in elite swimmers demonstrated that the decrease in negative influence of training with its progressive reduction during 3 or 4 wk resulted in around 3% improvement in performance (26). Such a duration for the taper period did not compromise the positive influence of training. Nevertheless, model limitations arise from the observed differences among published results (6,7,24). The comparison of the published model parameters showed that they could be dependent on the severity of the training doses (8). With greater and more frequent training doses, the model parameters would contribute to a greater magnitude and duration of the fatigue induced by each training bout. To explore this possible modification of the training response to a single training bout according to the past training doses, a recursive least squares algorithm was proposed to allow the model parameters to vary over time (8). A recent study using this algorithm showed that the increase in training frequency yielded a progressive increase in the magnitude and duration of the fatigue induced by a same training bout (5). A decrease in the gain of performance for a single training bout was also observed. The model initially proposed by Banister and coworkers could provide an imperfect description of training-induced fatigue produced by various work regimens. Consequently, a new formulation of the systems model is needed to take into account the increase in the fatigue effect resulting from repeated training sessions.

More precisely, the performance ascribed to system output was mathematically related to the training doses ascribed to system input. The model generally used in the literature is defined by a transfer function composed of two first-order filters where the impulse response is $k_1 e^{-t/\tau 1} - k_2 e^{-t/\tau 2}$. Response to training dose is characterized by the parameters of the two antagonistic first-order systems: i.e., two gain terms k_1 and k_2 and two time constants τ_1 and τ_2. To allow the dose-response relationship to vary between

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training dose and performance, the model development proposed in this study is that the gain term for the negative component varies with training doses according to a first order relationship. The gain term for the negative component would thus be a state variable varying with system input in which the impulse response is $k_3 e^{-t/\tau 3}$. The resulting impulse response of performance output to systems input would be $k_1 e^{-t/\tau 1} - k_2(t)e^{-t/\tau 2}$ in which the gain term for the negative component would vary over time with the repetition of training doses. The proposed nonlinear expression of the model would yield a performance response to a single training bout that would be dependent on the intensity of past training. Such a model would be, however, fundamentally different from the model with time-varying parameters using the recursive least square method (5,8). The model proposed in this study assumes that the gain term for fatigue effect is mathematically related to training dose using a first-order filter. Conversely, the time-varying parameters in the earlier model did not assume their variations over time. Leaving model parameters free to vary over time enabled posterior analysis of response to training (5,8). The reliability of the model proposed in this study would provide further evidence of a dose-response relationship varying over time according to the cumulative amount of training. Furthermore, a systems model that would better describe response to training could be a useful tool to study the importance of training periodization for optimizing performance improvement.

The aim of this study was thus to develop the systems model with time-invariant parameters by introducing variations in the fatiguing effect of a single training bout. To evaluate its reliability, the goodness-of-fit of performance using this extended model was compared with existing models. The refinement of the model introducing new parameters needs to be evaluated by testing whether the increase in model complexity would yield a significant better fit of performance response to training. The data used in this study were taken from a previous experiment (5). Because the point of the new formulation of the model is to better describe response to various training regimens, the different models were compared using a step increase in training after a period of adaptation to lower training doses. Another goal of this study was to determine whether the present data extrapolated to more intensified training could be compared with athletes' response to overtraining.

METHODS

Experimental methods. The experimental data were taken from a study entirely described in a previous report (5). Six healthy men volunteered for this experiment after giving their informed written consent. The study was approved by the local ethics committee (Conseil Consultatif de la Protection des Personnes dans la Recherche Biomédicale de la Loire). Mean age, weight, height, and maximal oxygen uptake before the study were respectively: 32.7 ± 5.0 yr, 83.5 ± 12.6 kg, 182 ± 8 cm, and 42.9 ± 7.4 $mL \cdot min^{-1} \cdot kg^{-1}$.

Throughout the experiment, the subjects performed trials to measure the maximal work they could develop for 5 min. After a 10-min warm-up, the subjects did an all-out exercise over 5 min on a cycle ergometer (Model 829E, Monark, Varberg, Sweden). The subjects adapted their pedaling frequency according to their own possibilities throughout the 5-min test. Breaking forces were predetermined from previous tests to keep average pedaling frequency around 70–80 RPM. The power output developed by the subjects was averaged over the 5-min test to estimate P_{lim5}' used as a criterion of performance. Measurement variability was estimated from four trials performed during the 2 wk preceding training intervention. Although no statistical difference was observed, the first value was discarded to take possible learning into account. The three remaining measurements of P_{lim5}' showed a 4.28 ± 1.94 W intra-individual variability. The 1.58 ± 0.81% coefficient of variation (CV%) is in keeping with the 1–3.5% range reported in the literature for such trials lasting 15–60 min (16,17,27).

After 2 wk with only performance measurements, the experiment included two periods of training: an 8-wk period with 3 training sessions per week (weeks 1–8) and a 4-wk period with 5 training sessions per week (weeks 10–13) separated by 1 wk without training (week 9). The last 2 wk of the experiment were also a period without training (weeks 14–15). During the first training period (weeks 1–8), the three weekly training sessions were generally separated by 2 d without training. Each day of training, the subjects performed first one test to measure P_{lim5}', and after 15 min of rest they trained on a cycle ergometer (Model 818, Monark) using intermittent exercise with 5 min of work interspersed with 3 min of active recovery repeated four times. Exercise intensity was prescribed to 85% of the last measured P_{lim5}'. During the second training period (weeks 10–13), the subjects trained 5 d consecutively per week. Every other day, they performed the same training session as during weeks 1–8. The two other days, the subjects did not perform the P_{lim5}' test but repeated the training sequence five times instead of four. The P_{lim5}' test was repeated two or three times for each week of the experiment. The subjects performed two tests the week before the experiment (week 0) and during week 9. P_{lim5}' was also measured three times during week 14 and twice during week 15. Additionally, tests to measure $\dot{V}O_{2max}$ were performed before the experiment and during weeks 9 and 15.

The daily training quantity was computed in arbitrary units from work done during training sessions and trials. The work done during warm-up and recovery was not considered in the computation. The tests to measure P_{lim5}' and $\dot{V}O_{2max}$ were both arbitrarily ascribed to 100 training units (t.u.). Each 5-min bout of exercise for training sessions was weighted by intensity referred to P_{lim5}' (i.e., mean power output/P_{lim5}' × 100). A training session composed of four bouts of exercise at 85% of P_{lim5}' would be thus ascribed to 4 × 85 = 340 t.u.

Mathematical modeling. Systems modeling for describing adaptations to training consists in mathematically relating change in performance (system output) to the amount of training (system input). The model generally used in the literature was initially proposed by Banister et al. (1). This model is defined by a transfer function composed of two first-order filters characterized by the two gain terms k_1 and k_2, and the two time constants τ_1 and τ_2 (Model 2-Comp). To test the statistical significance of the second component, the two-component model was compared with a systems model comprising only one first-order filter (Model 1-Comp) with an impulse response $k_1\ e^{-t/\tau 1}$ (7). Another third-order model (Model 3-Comp), proposed by Calvert et al. (10), has two negative components and one positive component to single out the fatigue effect on the time course of training adaptation. The impulse response of this systems model is $k_1\ (e^{-t/\tau 1} - e^{-t/\tau' 1}) - k_2\ e^{-t/\tau 2}$. For each model, the performance p(t) is obtained by the convolution product of the training doses w(t) with the impulse response added to basic level of performance noted p*. W(t) is considered to be a discrete function, i.e., a series of impulse each day, w^i on day i. The convolution product becomes a summation in which model performance $\hat{p}^n$ on day n is estimated by mathematical recursion from the series of w^i. $\hat{p}^n$ is thus estimated for models used in this study as follows:

$$\text{Model 1-Comp: } \hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i\ e^{-(n-i)/\tau_1} \tag{1}$$

$$\text{Model 2-Comp: } \hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i\ e^{-(n-i)/\tau 1} - k_2 \sum_{i=1}^{n-1} w^i\ e^{-(n-i)/\tau 2} \tag{2}$$

$$\text{Model 3-Comp: } \hat{p}_n = p^* + k_1 \sum_{i=1}^{n-1} w^i [e^{-(n-i)/\tau 1} - e^{-(n-i)/\tau' 1}] - k_2 \sum_{i=1}^{n-1} w^{ie^{-(n-i)/\tau 2}} \tag{3}$$

The model proposed in this study assumes that the gain term for the negative component is a state variable varying over time in accordance with system input. Performance output for the model proposed in this study is computed as follows

$$\hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i\ e^{-(n-i)/\tau 1} - \sum_{i=1}^{n-1} k_2^i\ w^i\ e^{-(n-i)/\tau 2} \tag{4}$$

in which, the value of k_2 at day i is estimated by mathematical recursion using a first-order filter with a gain terms k_3 and a time constant τ_3

$$k_2^i = k_3 \sum_{j=1}^{i} w^j e^{-(i-j)/\tau 3} \tag{5}$$

The parameters for the four models were determined by fitting the model performances to actual performances by the least square method. The set of model parameters was determined by minimizing the residual sum of squares between modeled and measured performances (RSS)

$$RSS = \sum_{n=1}^{N} [p^n - \hat{p}^n]^2 \tag{6}$$

where n takes the N values corresponding to the days of measurement of the actual performance. Successive minimization of RSS with a grid of values for each time constant gave the total set of model parameters.

The time response of performance to a single training bout was characterized by variables derived from model parameters. t_n, the time to recover performance and t_g, the time to peak performance after training completion were computed as

$$t_n = \frac{\tau 1\ \tau 2}{\tau 1 - \tau 2} \ln\left(\frac{k2}{k1}\right) \text{ and } t_g = \frac{\tau 1\ \tau 2}{\tau 1 - \tau 2} \ln\left(\frac{\tau 1\ k2}{\tau 2\ k1}\right) \tag{7}$$

p_g the maximal gain in performance for 1 unit of training is estimated by

$$p_g = k_1\ e^{-t_g/\tau_1} - k_2\ e^{-t_g/\tau_2} \tag{8}$$

Indexes of adaptation and fatigue were computed for the model proposed in this study from the output of the two antagonistic components a(t) and f(t)

$$a^n = k_1 \sum_{i=1}^{n-1} w^i\ e^{-(n-i)/\tau_1} \text{ and } f^n = \sum_{i=1}^{n-1} k_2^i\ w^i\ e^{-(n-i)/\tau_2} \tag{9}$$

To single out the short-term negative effect of the training doses from the long-term benefit, positive and negative influences of training on performance (ip and in, respectively) were estimated as previously described (6). The amount of training on day i had an effect on performance on day n quantified by

$$E(i/n) = k_1 w^i e^{-(n-i)/\tau_1} - k_2^i w^i\ e^{-(n-i)/\tau_2} \tag{10}$$

The values of in and ip on day n were estimated from the sum of influences of each past training amount depending on whether the result was negative or positive

$$in^n = \sum_{i=1}^{n-1} |E(i/n)|\text{, when } E(i/n) < 0 \tag{11}$$

$$ip^n = \sum_{i=1}^{n-1} |E(i/n)|\text{, when } E(i/n) > 0 \tag{12}$$

Model performance on day n was thus the difference between ip^n and in^n added to p*.

As a final study, sets of parameters were estimated for Model 2-Comp over both training sequences. Subjects' performance appeared to begin to plateau off before the step increase in training frequency during week 10. If the subjects reached their limits of adaptation, alterations of their responses to training could obscure the results of this study. To check whether the difference in fitness could affect the response to training doses, Model 2-Comp was applied separately for the two phases of training. The parameters were first estimated using data from preexperiment to week 9 including the 3 $d \cdot wk^{-1}$ training period. Another set of parameters were estimated using data from week 10 to 15 including the 5 $d \cdot wk^{-1}$ training period. The values of the variables reached at the end of the first period were used as initial values for the second period.

Statistics. Selected variables were expressed as means ± SD, and comparisons were done using paired *t*-test or ANOVA when appropriate. Indicators of goodness-of-fit

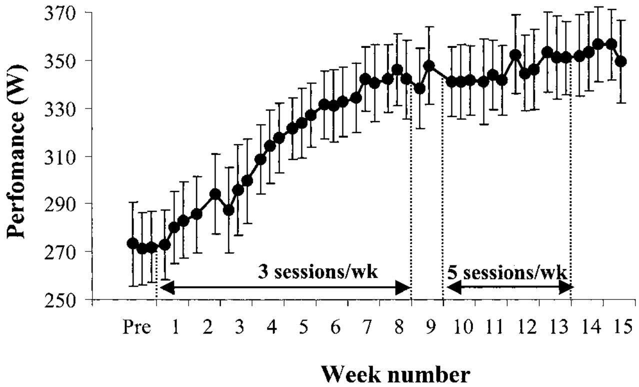

FIGURE 1—Pattern of performance measured with P_{lim5}' test over the experiment. *Dotted lines* delimit the two phases of training: phase 1 with three training sessions per week and phase 2 with five training sessions per week. Values are mean ± SE.

were estimated for each model used in this study. The statistical significance of the fit was tested by analysis of variance of the RSS in accordance with the degrees of freedom (*df*) of each model: $df = 2$ for Model 1-Comp, $df = 4$ for Model 2-Comp, $df = 5$ for Model 3-Comp and the model proposed in this study, and $df = 8$ for Model 2-Comp applied separately to the two training phases. The adjusted coefficient of determination (Adj. R^2) was computed to consider the differing *df* in the competing models. The mean square error on performance estimation (SE) was computed as $\sqrt{RSS/(N - DF - 1)}$, where *df* is the degree of freedom of the tested model. The level of confidence for each level of model complexity was tested by analysis of variance of the related decrease in residuals variation. The decrease in RSS explained by the introduction of further model parameters was tested using the *F*-ratio test in accordance with the increase in *df*.

RESULTS

Figure 1 shows the mean evolution of performance. The performance increased until week 7 and appeared to plateau during week 8. The mean improvement was 27 ± 7% when compared with preexperiment values. The performance increased then slowly with five training sessions per week. The total improvement in performance reached 30 ± 7% during week 13 when compared with initial level.

Table 1 compares the goodness of fit for the differing models applied in this study. Performance estimated with the systems model using only one first-order component exhibited a significant fit with measured data ($P < 0.001$ in each subject). Model 2-Comp improved the fit in three subjects ($P < 0.05$ in subjects 1 and 4 and $P < 0.001$ in subject 5). The three-component model proposed by Calvert et al. (10) did not yield further improvement in any subject. The model proposed in this study, where k_2 varied with training, significantly improved the performance fit in all subjects compared with Model 1-Comp ($P < 0.001$) and in five subjects compared with Model 2-Comp ($P < 0.001$ in all cases). No improvement in fit was observed only in subject 5 for whom the Model 2-Comp yielded the best fit to performance (Adj. $R^2 = 0.943$ and $P < 0.001$ compared with Model 1-Comp). Table 2 shows the estimates of the model proposed in this study. No difference was observed for the time constant τ_1 compared with Model 1-Comp and Model 2-Comp. However, the time constant τ_2 was statistically greater than the estimates produced by Model 2-Comp (7.0 ± 1.9 d, $P < 0.01$).

Figure 2 shows the fit of actual performance using the model proposed in this study for subject 4. The results showed how k_2 varied over the second period of training when training was repeated five consecutive days and the consequences of these variations on the indexes of adaptation and fatigue. During the first period of training, because k_2 was lower than k_1, the greater increase in a(t) than f(t) allowed performance to increase regularly with the succession of training sessions and the negative influence of training on performance (in) rarely exceeded 0. However, when training was performed each day of the week, k_2 increased up to values greater than k_1. This greater fatiguing effect of training prevented a regular increase in performance. The sum of negative influences of training on performance (in) reached values around 7 units over this second period of training.

Using Model 2-Comp over each training phase improved significantly the performance fit when compared with Model 2-Comp for the overall period ($P < 0.05$ in subject 5 and $P < 0.001$ in the remaining subjects). The fit was significantly improved in only four subjects when compared with the model proposed in this study ($P < 0.05$ in subjects 5 and 6, $P < 0.01$ in subject 1, and $P < 0.001$ in subject 2). The adjusted coefficient of determination was 0.953 ± 0.015 and the standard error of the fit 5.87 ± 0.77 W for the overall experiment. The parameter estimates were given for the two periods of training on Table 3. Despite greater fitness, both gain terms for the second period of training appeared to be greater than first period. However, the differences did not reach the limits of statistical significance ($0.05 < P < 0.1$). No statistical difference was observed for time constants between the two phases of training ($P > 0.2$).

DISCUSSION

The primary goal of this study was to verify the statistical adequacy of a systems model in which the gain term for negative effect of training was a state variable depending on the amount of past training. Such a model appeared to significantly improve the performance fit compared with current models using time-invariant gain terms for positive and negative components of training.

All systems models tested in this study enabled us to relate the changes in performance to training dose in each subject at $P < 0.001$. However, the adequacy of the level of complexity in each model structure should be analyzed. As previously shown for moderately active subjects (7), the two-antagonistic-component structure was not suitable in all subjects. The introduction of the second component, which appeared with a negative gain term, altered weakly the fit

TABLE 1. Indicators of goodness-of-fit of performance for various systems models of training effects.

Subject No.	*N*	Model-1Comp *df* = 2		Model-2Comp *df* = 4		Model-3Comp *df* = 5		Proposed Model *df* = 5	
		Adj.R^2	SE	Adj.R^2	SE	Adj.R^2	SE	Adj.R^2	SE
1	45	0.920	7.91	0.933*	7.26	0.933	7.26	0.958†,‡	5.73
2	45	0.883	10.97	0.896	10.37	0.897	10.25	0.954†,‡	6.86
3	40	0.807	12.35	0.817	11.98	0.816	12.04	0.947†,‡	6.43
4	45	0.815	10.51	0.850*	9.42	0.850*	9.43	0.931†,‡	6.39
5	46	0.860	9.13	0.943†	5.84	0.943†	5.83	0.944†	5.79
6	45	0.858	10.98	0.871	10.46	0.873	10.40	0.931†,‡	7.63
Mean ± SD		0.857 ± 0.042	10.31 ± 1.56	0.885 ± 0.048	9.22 ± 2.27	0.885 ± 0.049	9.20 ± 2.27	0.944 ± 0.011	6.47 ± 0.71

Model-1Comp, model using one first-order component; Model-2Comp, model using two first-order components; Model-3Comp, model using one first-order component and one second-order component; proposed model, model proposed in this study with two components where the gain term for negative component varies by using one further first-order filter; *N*, number of measurements of performance; Adj.R^2, adjusted coefficient of determination; SE, standard error. Statistical difference from Model-1Comp: * $P < 0.05$; † $P < 0.001$ and from Model-2Comp: ‡ $P < 0.001$.

obtained with only one component. The residual variations decreased significantly only in three subjects. Previous studies have shown that the introduction of the second component is suitable in more stressful training situations as observed in athletes (6,9,26). The model initially proposed by Calvert et al. (10), which included two negative components to single out fatigue response and delay in adaptation, was unsuitable for all subjects. When k_2 was assumed to increase with training volume/load using a first-order filter, the residual variations decreased significantly in each subject compared with Model 1-Comp and in five subjects compared with Model 2-Comp. The standard error of the performance fit decreased from 9.22 ± 2.27 W with Model 2-Comp to 6.22 ± 0.71 W with the model proposed in this study.

Training would have a negative influence on performance over the days after a training bout only when $k_2 > k_1$. This was the case in each subject of this study when they trained five consecutive days. This result is in keeping with those obtained using Model 2-Comp for more stressful training in athletes (2,4,26) or for controlled experiments in nonathletes (8,24). In these previous studies, model parameters indicated that training bouts would have a negative influence on performance for up to 1–2 wk after training completion. This greater time necessary to recover performance could be due to greater training accumulation with one or two sessions per day. The influence of training demands greater than those used in this study can be extrapolated from the model proposed in this study. Table 4 shows the variables derived from model parameters indicating the magnitude and duration of the negative influence of training on performance for different amounts of training. These data were computed for continuous stimulation, i.e., an identical training dose repeated each day, and for which the duration would be long enough for the subjects to reach a steady state. Equations 1 and 2 were used to compute the model-derived variables using for k_2 the value reached at each steady state. These data show that for daily training doses slightly greater than those used for this study (500 vs 400–450 t.u.), the time necessary to recover performance after training would reach a mean value of 2 wk as observed for stressful training. The consequence of this increase in fatiguing effect with training dose is that the relationship between daily training dose and performance would have an inverted-U shape as depicted in Figure 3. When using model parameters obtained for each subject, the maximal performance increment would be 128 ± 43 W for an optimal training of 322 ± 70 t.u. per day. The model outputs in Figure 3 were computed using parameters set to average values obtained in this study and referred to the optimal values of training and performance. Such a relationship would mean that when the amount of training exceeds the optimal level, performance could decline because of the fatigue induced by over-solicitation, as suggested in a previous report (18). Endurance performance in athletes has a tendency to plateau when compared with training volumes (13,20). Furthermore, doubling the amount of training in elite swimmers did not resulted in a performance enhancement greater than in a control group (11). Accumulation of large amounts of intensive exercise with insufficient recovery between training bouts could provide performance lower than expected. This transient decrease in performance with intensified training could be reversible with several days to several weeks of reduced training (14,18,19). This reversible stage has been termed overreaching. However, this could be a gradual transition to a more long-lasting stage referred to as overtraining syndrome or staleness (14,18,19). These data on overtraining are in line with the alterations in the derived variables using the proposed model.

The findings of this study indicate that for training doses above an optimal level, recovery phases would be required to maximize gain in performance. The question that arises from these data is whether the model proposed in this study would be adequate to describe the responses during the peaking period observed in athletes (25). To address this issue, the model was driven with the average-fit parameters obtained in this study to compare output with recently reported experimental data (15). In that previous report,

TABLE 2. Parameter estimates for the systems model proposed in this study.

	k_1 (a.u.)	k_3 (a.u.)	τ_1, (days)	τ_2, (days)	τ_3, (days)
Mean ± SD	0.031 ± 0.007	0.000035 ± 0.000010	30.8 ± 1.6	16.8 ± 3.3	2.3 ± 1.0

k_1, multiplying factor for the positive component of training; k_3, multiplying factor for the fatigue factor; τ_1, time constant of decay for the positive component of training; τ_2, time constant of decay for the negative component of training; τ_3, time constant of decay for the fatigue factor; k_1 and k_3 are expressed in arbitrary units (a.u.).

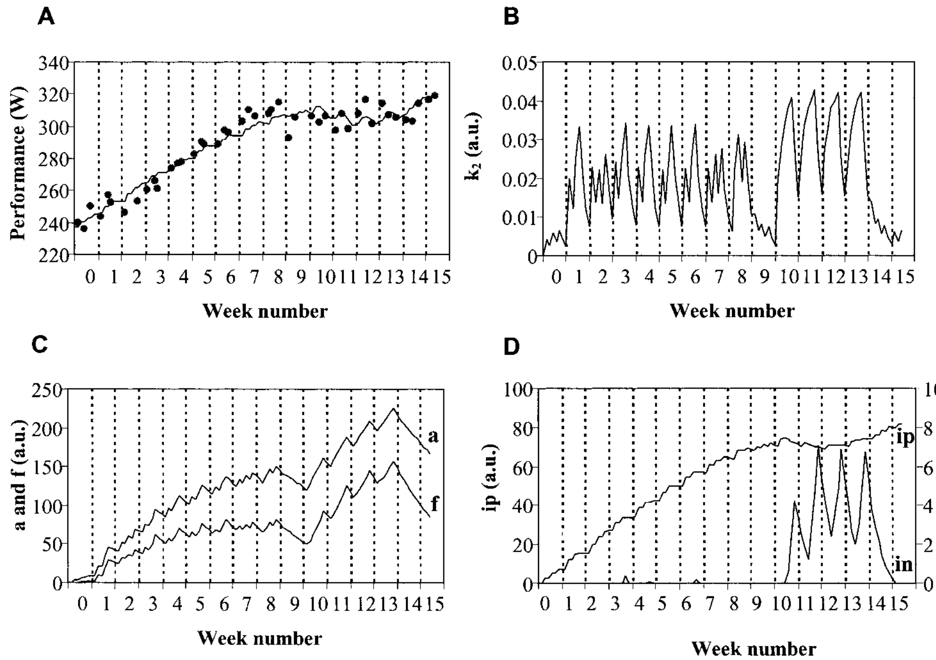

FIGURE 2—Results for subject 4. A. Pattern of measured performance around line of best fit for the model proposed in this study. Variations in model-derived variables: B. Gain term for negative component k_2. C. Outputs of positive and negative components, a and f, respectively. D. Sum of positive and negative influences of training on performance, ip and in, respectively; au, arbitrary units.

trained subjects had doubled the amount of their habitual training over 2 wk before reducing training to about half of their habitual training. Maximal aerobic power close to the performance criterion used in the present study decreased significantly during overload and returned to its initial level over the two weeks of recovery. The model proposed in this study was used to simulate performance under similar conditions. The simulations began at steady state with three training sessions per week corresponding to 450 t.u. The additive term was set at 240 W to give an initial level of performance close to 340 W. During intensified training, daily training (400 t.u. for each session) was maintained over 2 wk before reducing training to three sessions per week (200 t.u. for each). These training amounts were chosen according our study and would be lower than actual training reported in ref. 15. The resulting model simulations are depicted in Figure 4; agreement was good with the experimental data of Halson et al. (15) that showed a decrease in performance from 340 to 320 W with intensified training and recovery of initial level over 2 wk of reduced training. It is noteworthy that performance exceeded its initial level over the third week of reduced training.

The amounts of training in this study are, however, difficult to compare with other data. The method to quantify training is only adapted to this study. Because only work intensity could vary between training sessions, the computation allowed us to take any change in training amount into account. The arbitrary unit used in this study could be compared with training impulse (Trimp) calculating training quantity from duration and intensity of each phase of exercise (3). The 400–450 t.u. for each training session would represent around 100 Trimp. Previous application of Model 2-Comp to data of two subjects who trained 28 consecutive days with 100–150 Trimp each day yielded 8 and 11 d for t_n (24). These data are in line with those obtained with the model proposed in this study. Nevertheless, training amounts in these experiments appeared to be lower than in endurance athletes (2,4). Average training over 280 d in elite triathletes was 217 ± 34 Trimp per day (21). The value for optimal training found in this study should be greatly lower than usual training in athletes. Long-term adaptation could improve the tolerance to exercise repetition yielding to an increase in optimal training.

Other limits in the conclusions should be addressed according shortcomings inherent to model or arising from the design of the experiment. The great simplifications in training quantification and transfer function make hazardous extrapolation from modeled data to situations different than studied. Moreover, the fitness improvement and the training intensity could have an impact on the results of this study. The performance fit could be also improved by dividing the experimental period in two distinct phases in accordance with training. This is an additional issue to show that Model 2-Comp could be imperfect to describe response to training with various regimens. Nevertheless, the initial question that arose from the results was whether the difference in fitness between the two training phases could have flawed the

TABLE 3. Parameter estimates using the two-component model throughout each phase of training: period 1, preexperiment to week 9; period 2, week 10–15.

		k_1 (a.u.)	k_2 (a.u.)	τ_1 (days)	τ_2 (days)	SE (W)
Period 1	Mean ± SD	0.0193 ± 0.0059	0.0148 ± 0.0085	40.8 ± 15.0	9.0 ± 6.0	5.66 ± 1.30
Period 2	Mean ± SD	0.0211 ± 0.0065	0.0209 ± 0.0056	35.0 ± 12.2	12.7 ± 2.6	6.36 ± 0.49

k_1, multiplying factor for the positive component of training; k_2, multiplying factor for the negative component of training; τ_1, time constant of decay for the positive component of training; τ_2, time constant of decay for the negative component of training; τ_2, time constant of decay for the negative component of training; k_1 and k_2 are expressed in arbitrary units (a.u.); SE, standard error.

TABLE 4. Means ± SD for variables derived from model parameters for steady state with a same training dose repeated each day.

Daily Training Amounts (t.u.)	k_2, (a.u.)	k_2/k_1	t_n, (days)	t_g, (days)	p_g, (a.u.)
300	0.028 ± 0.006	0.91 ± 0.12	0.2 ± 0.4	7.0 ± 10.0	0.0059 ± 0.0027
400	0.037 ± 0.007	1.21 ± 0.16	5.9 ± 3.8	28.2 ± 3.8	0.0053 ± 0.0006
500	0.046 ± 0.009	1.51 ± 0.20	15.1 ± 4.4	37.4 ± 5.7	0.0040 ± 0.0009

t.u., arbitrary units used for training dose; k_2, fatigue factor, i.e., multiplying factor for the negative component of training in arbitrary units (a.u.); k_2/k_1, ratio between multiplying factors for positive and negative components of training (dimensionless); t_n, time needed after training to allow performance to return to its initial level; t_g, time needed after training to allow performance to reach maximal level; p_g, maximal gain in performance for 1 unit of training in arbitrary units (a.u.).

outcomes of this study. The higher fitness during the second training period did not appear to yield to a diminished positive response to training doses. The gain terms for adaptation and fatigue were both slightly greater for the second period of training. The difference between training phases did not reach, however, the limits of statistical significance. With Model 2-Comp, when performance reached a steady state with constant training, effect of each training dose should remained unchanged to allow adaptations to be maintained. The assumptions underlying the development of the proposed model was also based on data indicating that the fatigue influence of exercise bouts should be greater for greater training amounts (8). Moreover, the data of this study were analyzed using a model with parameters free to vary over time without any assumption on these variations (5). This previous report showed that gain term for adaptation did not appear to decrease as fitness increased or when training was steeply increased. The better fit of performance with fatigue factor varying with training could not be thus attributed to a decrease in positive effect of training due to higher fitness.

Another concern involves the type and the number of performance trials. The precision and frequency of performance measurement was necessary to accurately model the responses to training. The total number of measurements also increased the power of the statistical analysis to test the confidence of the decrease in residual variation with increasing model complexity. The frequency of performance testing was the same for the two phases of training and the phases without training. Three tests per week to measure P_{lim5}' could cause, however, a high-intensity-orientated training program. Although the amount of high-intensity work could appear unusual, the subjects tolerated well this work regimen because performance increased regularly during the first sequence of training. In our previous report (5), we indicated that $\dot{V}O_{2max}$ increased by 20.5 ± 7.0% after the first phase of training ($P < 0.001$). Data of this study could, however, be dependent on this particular feature of the experiment. Further studies using lower intensity for exercise are needed to determine how the model proposed in this study would describe response to training using other combination of work volume and intensity.

In conclusion, the nonlinear model proposed in this study appeared to describe the responses to training more precisely than previous models. The present data suggest an inverted-U-shape relationship between daily amounts of training and performance. Furthermore, these data would be helpful to extrapolate response to training using more intensified work or varied regimens. Nevertheless, model shortcomings would limit prediction to training situation close to our experiment, i.e., a step increase in training over a short period. Difference in training strategy or long-term adaptation could affect the responses in a manner different than model prediction.

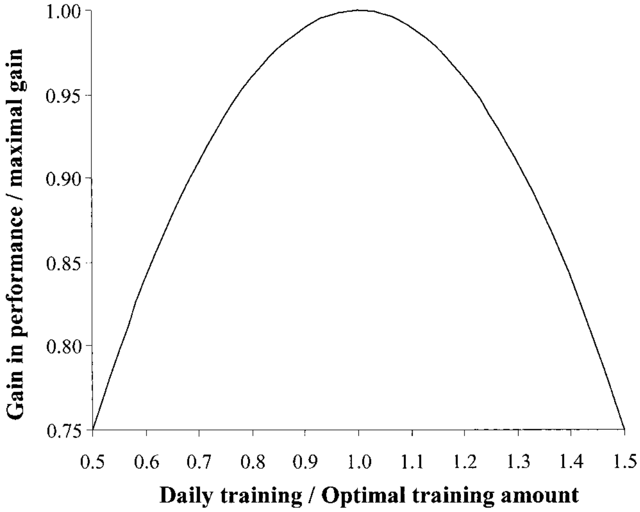

FIGURE 3—Gain in performance at steady state for a same training amount repeated each day. Performance gain was expressed according its maximal value. Training amount was referred to optimal training yielding maximal gain in performance. Computations were made with the model proposed in this study with τ_1 = 30 d, τ_2 = 17 d, τ_3 = 2 d, k_1 = 0.03 arbitrary units, and k_3 = 0.000035 arbitrary units.

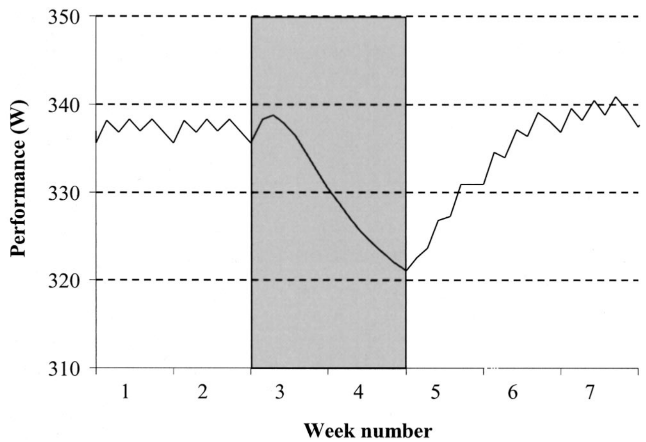

FIGURE 4—Variation over time in performance. Weeks 1 and 2: steady state with training doses of 450 t.u. 3× wk^{-1}. Weeks 3 and 4: overtraining with a daily training dose of 400 t.u. Weeks 5–7: recovery with training doses of 200 t.u. 3× wk^{-1}. Computations were made with the model proposed in this study with τ_1 = 30 d, τ_2 = 17 d, τ_3 = 2 d, k_1 = 0.03 arbitrary units, k_3 = 0.000035 arbitrary units, and p* = 240 W.

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