Effects of training frequency on the dynamics of performance response to a single training bout

THIERRY BUSSO,1 HENRI BENOIT,1 RÉGIS BONNEFOY,1 LÉONARD FEASSON,1 AND JEAN-RÉNE LACOUR2

1Groupe Physiologie et Physiopathologie de l’Exercice et Handicap, Groupement d’Intérêt Public “Exercice,” Université Saint-Etienne, 42023 Saint-Etienne cedex 2; and 2Laboratoire de Physiologie, Faculté de Médecine Lyon 1, 69921 Oullins cedex, France

Address for reprint requests and other correspondence: T. Busso, Laboratoire de Physiologie, CHU de Saint-Etienne, Hôpital de Saint-Jean-Bonnefonds, Pavillon 12, 42055 Saint-Etienne Cedex 2, France (E-mail: busso@univ-st-etienne.fr).

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IT IS GENERALLY ASSUMED THAT training adaptations occur subsequent to exercise-induced modifications of cellular homeostasis. These exercise-induced changes would be the main stimulus driving the physiological responses leading to the body’s adaptations (25, 26). Nevertheless, overloading for a long period might produce the persistent fatigue generally associated with so-called overtraining (10, 15, 16, 18). Short-term overtraining or overreaching should be distinguished from long-term overtraining, also called overtraining syndrome or staleness. Overreaching is characterized by a transient decline in performance that, after few days or few weeks of less intensive training, can be recovered, sometimes at a level even higher than that attained before the overload. Inversely, overtraining syndrome or staleness is characterized in athletes by an incapacity to train and perform over a longer period. A few weeks or months without intensive training would be necessary to recover normal training capacity. Although very little is known about the physiological mechanisms of overreaching and staleness, there is evidence that an imbalance between training loads and recovery time could be a major cause of the temporary incapacity to perform.

To analyze the adaptations occurring during physical training and exercise-induced fatigue, several studies have used various systems modeling the effects of training on performance (1–8, 20, 22). These studies have considered performance as a systems output varying over time according to the training loads (i.e., systems input). According to systems modeling, performance is mathematically related to quantified training via a transfer function, including two first-order filters. The first filter with a positive gain is ascribed to training adaptations. The second filter with a negative gain is ascribed to the fatiguing effects of exercise. The shorter time constant of the negative function, compared with the positive function, accounts for the transient decline in performance after exercise completion. The model parameters (gain terms and time constants) are determined by fitting model performances to experimental data. Comparison of the model parameters has shown differences that would arise from differences in the training regimen (6). Differences in the time needed to recover performance after training completion were reported with values ranging from 1–3 days for subjects training four times a week (5) to 23 days for an elite athlete training once or twice a day (4). These differences could arise from the frequency and the size of the training loads. The repetition of training loads could alter the response to a given training dose. If exercise occurs before complete recovery from previous
exercise, the time necessary to recover could be longer than if there were a longer gap between the two training loads. Exercise-induced fatigue would thus be amplified by the repetition of stressful training bouts. To analyze more precisely the influence of training intensity on the time needed to recover, the systems model described above was modified in earlier work (6). A recursive least squares algorithm, used to introduce time-dependent variations into model parameters, was applied to data of strenuous training performed by two volunteers. This study showed that time-dependent variations in model parameters generally would not arise from noise in data. As suggested above, the observed changes in model parameters pointed out a possible increase in the magnitude and time course of long-term fatigue with repeated training loads (6).

The purpose of the present investigation was to analyze the dynamic variations of performance response to exercise with stepwise changes in training frequency. Changes over time in the responses to training loads were assessed using the systems model with time-varying parameters. More precisely, the aim of this study was to determine whether an increase in training frequency and thus a decrease in recovery time between training sessions would induce a progressive increase in the magnitude and duration of long-term fatigue induced by an identical training load.

METHODS

Subjects and experimental methods. Informed consent to participate in the study was obtained from six healthy men. All were sedentary or involved in recreational activities, and none was engaged in physical activity on a regular basis for at least 6 mo before the experiment. The protocol was approved by the local ethics committee (Conseil Consultatif de la Protection des Personnes dans la Recherche Biomédicale de la Loire). Mean age, weight, and height were, respectively, 32.7 ± 5.0 (SD) yr, 83.5 ± 12.6 kg, and 182 ± 8 cm.

Throughout the experiment, the subjects performed incremental tests until exhaustion to measure their maximal oxygen consumption ($\dot{V}O_2$ max) and trials to determine the maximal power that they could sustain for 5 min ($P_{lim\;5}$). $\dot{V}O_2$ max was measured during incremental exercise on a cycle ergometer (model 818, Monark, Stockholm, Sweden). Subjects warmed up for 5 min at a work rate ranging from 100 to 150 W, according to their fitness. The work rate was then increased every 2 min by 30 W until exhaustion. A 20-W increment was used for the preexperiment measurement in one subject who had a maximal aerobic power (MAP) equal to 200 W. The subjects breathed through a two-way non-rebreathing valve (model 2700, Hans Rudolph, Kansas City, MO). The expiratory gases were collected in a polyethylene bag (HP Production, Saint-Etienne, France) during the last 30 s of each 2-min bout. Gas composition was analyzed using a paramagnetic analyzer for $O_2$ (Servomex Serie 1440, Crowborough, UK) and an infrared analyzer for $CO_2$ (Datex Normocap, Helsinki, Finland). The gases in the bag were emptied in a Tissot spirometer (Techmachine Gymrol, Andrézieux, France) to measure minute ventilation. The external MAP was computed from power output and duration of the last increment as proposed by Kuipers et al. (17). Three minutes after cessation of exercise, a fingertip blood sample was taken to be analyzed for lactate concentration (YSI 2300, Yellow Springs Instruments, Yellow Springs, OH).

The trial to measure $P_{lim\;5}$ consisted of a 10-min warm-up and then an all-out exercise over 5 min on a cycle ergometer (model 829E, Monark). Breaking force was predetermined, and the pedaling frequency was adapted by the subject according to his own possibilities. The breaking force during the warm-up was equal to 50% of the breaking force during the subsequent 5-min test. To obtain a pedaling frequency around 70–80 rpm during the 5-min test, the breaking force was estimating using either the limit power obtained from the previous test or the MAP from the first test. The power output developed by the subject during the trial was registered throughout via an interface between the cycle ergometer and the computer. $P_{lim\;5}$ was determined as the average power output sustained over the test.

During the 2 wk preceding the training intervention, $\dot{V}O_2$ max was measured, and the subjects performed three trials to measure $P_{lim\;5}$. The training intervention was then composed of four periods: 1) an 8-wk period with three training sessions per week [low-frequency training (LFT), weeks 1–8]; 2) a 1-wk period without training (week 9); 3) a 4-wk period with five training sessions per week [high-frequency training (HFT), weeks 10–13]; and 4) a 2-wk period without training (weeks 14 and 15). During LFT, the three training sessions were generally separated by 2 days without training. On each day of training, the subjects performed first one test to measure $P_{lim\;5}$, and, after 15 min of rest, they trained on a cycle ergometer 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 $P_{lim\;5}$. During HFT, the subjects trained for 5 days consecutively per week. On Monday, Wednesday, and Friday, they performed the same training session as during LFT. On Tuesday and Thursday, the subjects did not perform the test to measure $P_{lim\;5}$ but repeated the training sequence five times instead of four. During the week between LTF and HFT, the subjects performed two tests to measure $P_{lim\;5}$ and one test to measure $\dot{V}O_2$ max. During the period subsequent to HFT, $P_{lim\;5}$ was measured three times during the first week and twice the second week. $\dot{V}O_2$ max was measured at the end of the last week of the experiment. These two $\dot{V}O_2$ max tests were done 2 days after the last $P_{lim\;5}$ measurement. Therefore, $P_{lim\;5}$ was measured two or three times for each week of the experiment, and $\dot{V}O_2$ max was measured on three separated occasions: before the experiment, after LFT, and after HFT.

Criterion performance and quantification of training. $P_{lim\;5}$ was used as a criterion of performance for modeling. The amount of training was quantified from work done during training and trials. The daily quantity of training was computed as a function of the exercise duration and the intensity referred to $P_{lim\;5}$. The work done during warm-up and recovery was not considered in the computation. The test to measure $P_{lim\;5}$ (i.e., 100% intensity) was ascribed to 100 training units. For training sessions, each 5-min bout of exercise was weighted by intensity of the effort (power output/$P_{lim\;5} \times 100$). For example, the work done during a training session composed of four repetitions of a 5-min effort at 85% of $P_{lim\;5}$ would be $4 \times 85 = 340$ training units. For the test to measure $\dot{V}O_2$ max, the amount of training was set at 100 units as for the trial to measure $P_{lim\;5}$.

Modeling training effects on performance. The model used in this study was entirely described in a previous study (6). The model is based on a systems model initially proposed by Banister et al. (1). The subject is represented by a system with a daily amount of training as input and performance as output. The system operates in accordance with a transfer
Maximal gain in performance; where \( g(\cdot) \) is the impulse response of the transfer function, \( k_1 \) and \( k_2 \) are gain terms, \( t \) is time, and \( \tau_1 \) and \( \tau_2 \) are time constants. Figure 1 shows that the impulse response of performance in case \( k_2 \) is greater than that in case \( k_1 \) and that \( \tau_1 \) is greater than \( \tau_2 \). After training completion, the decline in performance is given by \( k_2 - k_1 \). Afterward, recovery allows the performance to return to its initial value (time noted \( t_n \)) and then to peak at a maximal value (time noted \( t_g \)). The maximal gain in performance \( t_g \) days after a training load of 1 training unit is noted \( p_n \). These notations were chosen according to previous studies (6, 9).

The time functions of performance \([p(t)]\) and training \([w(t)]\) are mathematically related as

\[
p(t) = p^* + w(t)g(t)
\]

where \( p^* \) is an additive term that depends on the initial training status of the subject and \( * \) denotes the product of convolution.

The definition of the convolution product leads to

\[
p(t) = p^* + \int_0^t w(t - t')g(t')dt'
\]

Discretization of Eq. 3 results in an estimation of the model performance on day \( n \) \((p_n)\) from the successive training loads \( w_i \), with \( i \) varying from 1 to \( n - 1 \)

\[
p_n = p^* + k_1 \sum_{i=1}^{n-1} w_i e^{-\alpha - i\tau_1} - k_2 \sum_{i=1}^{n-1} w_i e^{-\alpha - i\tau_2}
\]

For the time-varying model, the parameters were fitted by using a recursive least squares algorithm with an exponential window (6). The model parameters were evaluated on each day that performance was measured. The parameters at a given time were estimated from the previous and present data. On day \( n \), the parameters are obtained by minimizing the following recursive function

\[
S_n = S_{n-1} - \alpha + (\hat{p}_n - p_n)^2
\]

where \( \alpha \) is a constant with a value ranging between 0 and 1. \( S_n \) was minimized for each day when actual performance was measured. The model parameters for the day \( n \) were estimated with successive minimization of \( S_n \) using a grid of values for the time constants: from 30 to 60 days for \( \tau_1 \) and from 1 to 20 days for \( \tau_2 \). The model parameters \((k_1, k_2, \tau_1, \tau_2)\) were initialized with the six values for performance measured during the preexperiment and the first week of training using the least squares method. The value of \( \alpha \) for the set of subjects was chosen so that the mean SE of the fit remained higher than the mean intrindividual variability of \( P_{\text{lim}}^5 \) assessed from the SD values computed before the training experiment.

The \( t_n \) was defined as the time needed after an impulse training stimulus for the effects of fatigue to be dissipated sufficiently to allow the effects of training to return performance to the pretraining level. Therefore, the performance exceeds its pretraining level. The \( t_n \) was estimated by

\[
t = \frac{\tau_1 \tau_2}{\tau_1 - \tau_2} \ln \left( \frac{k_2}{k_1} \right)
\]

The time needed to reach maximal performance after an impulse training stimulus \((t_g)\) was estimated as follows

\[
t = \frac{\tau_1 \tau_2}{\tau_1 - \tau_2} \ln \left( \frac{\tau_1 k_2}{\tau_2 k_1} \right)
\]

The maximal gain in performance due to 1 unit of training \((p_g)\) was estimated as follows

\[
p_g = k_2 e^{-\alpha \tau_1} - k_2 e^{-\alpha \tau_2}
\]

An additional analysis was undertaken to assess the specific effect of variations in time constants on results. For this, variations in performance were modeled with fixed time constants: 30 days for \( \tau_1 \) and 10 days for \( \tau_2 \). In this computation, only the gain terms were free to vary over time, using the same procedure as described above.

**Statistics.** Means, SD, and SE were computed for the selected variables, and the coefficients of variation (\%CV) were computed for each subject for \( P_{\text{lim}}^5 \) measured before the beginning of training. One-way ANOVA was used to test differences in the studied variables occurring during the experiment. The parameters measured during the \( V_{\text{O2 max}} \) test and the closest measurement of \( P_{\text{lim}}^5 \) (preexperiment, after LFT and after HFT) were compared with ANOVA and the Scheffé post hoc test. The differences in model parameters \((k_1, k_2, \tau_1, \tau_2, t_n, t_p, k_2 - k_1, \) and \( p_g) \) were examined after averaging the values over each week of the experiment. To discard the variability during the first weeks due to the initialization of the model parameters, ANOVA was applied to the values from the second week of the experiment. The variations in model parameters were examined first over LFT \((\text{weeks 2–8})\) and then over the entire experiment \((\text{weeks 2–15})\). The variations over time were examined with contrast analysis (Scheffé's method) to compare each value for \( \text{weeks 9–15} \) with the mean value over \( \text{weeks 2–8} \).

**RESULTS**

Measurement variability was estimated from the \( P_{\text{lim}}^5 \) tests run during the 2 wk preceding the experi-
Table 1. Measurement of maximal aerobic power and performance during the experiment

<table>
<thead>
<tr>
<th></th>
<th>Preexperiment</th>
<th>After LFT</th>
<th>After HFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO2max, l/min</td>
<td>3.52 ± 0.37</td>
<td>4.23 ± 0.42‡</td>
<td>4.30 ± 0.38§</td>
</tr>
<tr>
<td>VO2max, ml·min⁻¹·kg⁻¹</td>
<td>42.9 ± 7.4</td>
<td>50.5 ± 9.4‡</td>
<td>51.9 ± 9.0‡</td>
</tr>
<tr>
<td>Peak heart rate, beats/min</td>
<td>193.5 ± 7.6</td>
<td>189.7 ± 7.9</td>
<td>188.2 ± 8.4§</td>
</tr>
<tr>
<td>Peak blood lactate, mM</td>
<td>11.5 ± 1.3</td>
<td>15.5 ± 1.4‡</td>
<td>14.7 ± 1.7‡</td>
</tr>
<tr>
<td>MAP, W</td>
<td>267 ± 39</td>
<td>332 ± 34‡</td>
<td>340 ± 35‡</td>
</tr>
<tr>
<td>Plim5, W</td>
<td>275 ± 38</td>
<td>348 ± 40‡</td>
<td>355 ± 37‡</td>
</tr>
</tbody>
</table>

Values are means ± SD. LFT, low-frequency training; HFT, high-frequency training; VO2max, maximal oxygen consumption; MAP, external maximal aerobic power; Plim5, maximal power sustained for 5 min. Statistical difference from the preexperiment value: *P < 0.05; †P < 0.01; ‡P < 0.001.

ment and the test done on the first day of LFT (i.e., before any training). The first measurement was discarded to take learning into account. The variability for the three remaining values ascribed to the CV (SD/ mean × 100) was 1.58 ± 0.81% (SD = 4.28 ± 1.94 W).

Table 1 shows the gain in MAP and Plim5 after LFT and HFT. VO2max increased by 20.5 ± 7.0% after LFT (P < 0.001) and by 22.6 ± 5.0% after HFT (P < 0.001), compared with preexperiment levels. MAP increased by 25.7 ± 12.1 and 28.6 ± 13.7% after LFT and HFT, respectively (P < 0.001). The time course of Plim5 for each subject is given in Fig. 2. When the closest measurements to each VO2max test are analyzed, the statistical analysis showed a significant increase in Plim5 compared with preintervention values: 26.9 ± 6.7% after LFT and 29.5 ± 5.3% after HFT (P < 0.001). The postexercise blood lactate concentration also increased significantly after LFT (P < 0.001) and after HFT (P < 0.01). There was no statistical difference between the values obtained after LFT and HFT in any of the above variables. However, peak heart rate decreased significantly after HFT compared with the preintervention value (P < 0.05).

Fit of performances measured throughout the study for each subject to the model with time-varying parameters is illustrated in Fig. 2. For all of the subjects, the fit was better during LFT than during HFT when the day-to-day variations of Plim5 were greater. Table 2 gives the statistics of the fit of the model with time-varying parameters using a value of 0.95 for the weighting factor α. The coefficient of determination ranged from 0.957 to 0.982, and the SE was 4.76 ± 0.84 W. This 0.95 value for α was retained because the SE of the fit remained higher than the average SD of Plim5 measurements done before training.

Figure 3 shows the variations over time of the model parameters (k1, k2, τ1, and τ2) and their derived variables (tn, tg, k2 - k1, and pg). When only LFT (weeks 2–8) is considered, no statistical difference was observed for any variable. When the values from weeks 2–15 were analyzed using ANOVA, statistical differences were observed for k1, k2 - k1, and pg. The difference between the two gains k1 and k2 was greater than during LFT in week 11 (P < 0.05), week 12 (P < 0.001),...
and week 13 ($P < 0.05$). The time necessary to recover performance after training completion, $t_n$, increased significantly during HFT. With a mean value lower than 1 day during LFT (0.9 ± 2.1 days in week 8), $t_n$ increased to 2.3 ± 1.8 days in week 11 ($P < 0.05$), 3.5 ± 1.6 days in week 12 ($P < 0.001$), and 3.6 ± 2.0 days in week 13 ($P < 0.001$). The maximal gain in performance after a training dose of 1 unit, $p_g$, decreased progressively during HFT. However, the decrease was statistically significant only for weeks 14 and 15 after HFT ($P < 0.01$). The increase in $t_g$, the time necessary for performance to reach its maximal level after training completion, was not statistically significant. To illustrate these variations in model parameters, the im-

Table 2. Statistics of the time-varying model for the 6 subjects

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>$N$</th>
<th>Model With Time-Varying Time Constants and Gain Terms</th>
<th>Model With Only Time-Varying Gain Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coefficient of determination ($r^2$)</td>
<td>SE</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>0.982</td>
<td>3.92</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>0.980</td>
<td>4.74</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>0.972</td>
<td>4.98</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>0.957</td>
<td>5.28</td>
</tr>
<tr>
<td>5</td>
<td>46</td>
<td>0.979</td>
<td>3.69</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>0.962</td>
<td>5.93</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td></td>
<td>0.972 ± 0.010</td>
<td>4.76 ± 0.84</td>
</tr>
</tbody>
</table>

$N$, number of performance measurements.

Fig. 3. Variations in parameter estimates and derived variables (mean value per week ± SE) when a model with time-varying time constants and gain terms is used. A: time constant $\tau_1$; B: time constant $\tau_2$; C: $k_1$; D: $k_2$; E: $t_g$; F: $t_n$; G: $p_g$; H: $k_2 - k_1$, au, Arbitrary units. Significant difference: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. 

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pulse responses of performance (i.e., variations over time of performance after a training dose of 1 unit) using mean model parameters for the first week of HFT (week 10) and the third and fourth weeks of HFT (weeks 12 and 13) are compared in Fig. 4. The comparison of these responses showed 1) an increase in the decrement in performance after training completion for weeks 12 and 13 compared with week 10, 2) a progressive increase in the time needed to recover the initial level of performance from week 10 to 13, and 3) a decrease in the maximal gain in performance after recovery in week 13, although this decrease appeared to be statistically significant only 1 wk later.

As a final study, the time-varying model was applied to the data with only the gain terms free to vary over time and the time constants fixed to constant values: 30 days for $\tau_1$ and 10 days for $\tau_2$. The value for $\alpha$ was set at 0.94 to obtain a SE close to the results of the model with time-varying gains and time constants. Indeed, the coefficient of determination ranged from 0.958 to 0.980 and the SE was $4.81 \pm 0.68$ W (Table 2). The variations over time of the gains and the derived variables are depicted in Fig. 5. Despite the lack of variation in time constants, the gain terms and the derived variables ($t_n$, $t_g$, $k_2 - k_1$, and $p_g$) showed patterns similar to those with the free-varying time constant model. Additionally, a relationship between gain terms was observed for each subject when the values averaged over each week from week 2 were used. The negative gain $k_2$ was correlated with the positive gain $k_1$ in each of six subjects, with $r^2$ ranging from 0.66 to 0.97 ($P < 0.001$). The mean linear regression coefficients were $1.837 \pm 0.363$ for the slope and $-0.023 \pm 0.012$ for the intercept.

**DISCUSSION**

The major finding of this study was that an increase in training frequency induced changes in the dynamics of performance.
of performance response to a single training bout. There was 1) an increase in the magnitude and duration of the fatiguing effect for a single training session and 2) a decrease in exercise-induced adaptation assessed by the maximal gain in performance for a given amount of training.

The time course of performance during the experiment assessed by the limit power over 5 min showed a regular increase during the 8 wk of LFT. During HFT, in which recovery time between training sessions was diminished, day-to-day variations were clearly observed. The 26.9 ± 6.7% increase in Plim 5 after LFT over the preexercise value was comparable to the 25.7 ± 12.1% increase for MAP. However, the increase in the time trial result was slightly greater than the 20.5 ± 7.0% gain in VO₂ max. Although VO₂ max appeared to be the main determinant, other factors played a role in the gain in Plim 5. This greater improvement in Plim 5 than in VO₂ max could be explained by an amelioration of the net efficiency or a greater contribution with training of the anaerobic metabolic pathway. An increase in the anaerobic contribution would be in accordance with the increase in peak blood lactate after the VO₂ max trial (15.5 ± 1.4 mM after LFT vs. 11.5 ± 1.3 mM during preexercise; P < 0.001). These results were in line with those obtained after HFT, although no statistically significant further improvement was observed.

The systems model with time-varying parameters was applied with a recursive least squares algorithm (6). The 0–1 range assigned to the recursive algorithm’s parameter α enabled changes in model parameters. Setting α too small would allow rapid changes in model parameters, making them overly sensitive to noise in performance evaluation. Inversely, if time constants were free to vary over time or when they were kept constant. Using the model with only time-varying gain terms would thus be helpful in further investigations. However, it is difficult to interpret the correlation observed between the two gain terms. The structure of the model being the sum of two exponentials, variations in k₁ might compensate in part for variations in k₂. The more composite variables derived from model parameters would provide a clearer picture of the response to exercise. With the use of time-varying gain terms and time constants, statistical differences were observed between LFT and HFT for 1) the difference between the two gains k₂ and k₁, which reflects the magnitude of the decrement in performance after exercise completion, and 2) tn, which is the time needed to recover performance after exercise completion. These differences were statistically significant for the second to fourth weeks of HFT compared with mean values for LFT. The pg decreased progressively during HFT. However, this decrease became statistically significant only during the subsequent 2 wk without training.

Our observation that more frequent training yields a greater fatiguing effect is in accordance with data in the literature about modeling of training effects on performance. As noted in a previous study (6), differences in time-invariant parameters of the systems model would arise from differences in training intensity. The time to recover performance after exercise, assessed from model fitting, ranged from 1–3 days for subjects performing endurance training four times a week (5) to 23 days for an elite explosive athlete who trained once or twice a day (4). Values of 12.2 ± 5.7 days have been reported for elite swimmers (22) and 8 and 11 days for two subjects training once a day for 28 days (20). These differences in time to recover performance after training completion could be related to workload and training frequency (6). The results of this study are in line with these conclusions. The increase in training frequency yielded a significant increase in the time necessary to recover performance after a single training bout. The values obtained for tn, when the subjects trained 5 days a week, were lower than data in the literature for the time-invariant model. The lower
workloads compared with the previous experiments could explain this gap. The $t_n$ values increased up to 10 and 14 days for the two subjects studied in our laboratory's previous study (6). Although these two subjects also trained 5 consecutive days per week, their daily training doses were about twice those in the present investigation. High-dose training added to HFT could thus explain the high values for $t_n$ in athletes or during intensive training reported in the above-cited studies. Data reported for $t_n$ computed with time-varying or time-invariant models are in accordance with short-term overtraining lasting a few days to a few weeks (10, 15, 16, 18). However, considering their initial fitness, the subjects of this study could behave differently from well-trained elite athletes. Higher fit subjects could better tolerate the training sequences used in this study. The data of this study could not thus be directly translated to elite athletes. Nevertheless, the high $t_n$ values reported above in elite athletes would not be simply the time necessary to recover after a single training bout but the result of the repetitions of training loads. The new insight arising from the results of this study is that long-duration fatigue associated with short-term overtraining would be a progressive process in which the magnitude and duration of exercise-induced fatigue would increase with the repetition of the training doses. The time needed to recover could thus progressively increase up to 2–3 wk as reported for strenuous training. This period, ranging from a few days to a few weeks, would be the ideal period for tapering, which is the period of reduced training used to optimize performance for a competition (12, 21, 23).

The decrease in the maximal gain in performance for a given amount of training has been less well documented. This observation is in line with the conclusions that Wenger and Bell (27) drew from data pooled from training protocols, with training frequency ranging from two to six sessions per week. These authors showed that the optimal combination of intensity and frequency of training is 90–100% $\text{VO}_2\text{max}$ at a frequency of four sessions per week and that training effects plateau with higher frequencies. A possible limitation of the body to adapt to training loads could yield an apparent decline in the benefit of a new training stimulus. A progressive decrease in exercise-induced adaptation could also be associated with overtraining. Long-term overtraining is associated with a lack of adaptation to training loads, yielding underperformance and necessitating reduced training for weeks or months before recovering performance level. Although the underlying mechanisms of long-term overtraining are unclear, alterations of the body’s response to disturbed homeostasis could affect the capacity of overtrained subjects to recover and adapt to exercise (15).

Previous studies using the time-invariant model showed both lower $p_e$ and higher $t_n$ with increasing training load (6). However, differences in the initial level of fitness could explain these differences. The lower $p_e$ for the more fit subjects could be essentially due to the need for greater training loads to obtain similar or even lower gain in performance. The decrease in aerobic performance increment with training when fitness level increases was well documented (see, for example, Ref. 27). This phenomenon could obscure the findings of this study. The results about HFT could be different if HFT were done first before the increment in fitness. Because the subjects undertook HFT after LFT, the much higher fitness could be responsible for the observed decrease in $p_e$ during HFT. Nevertheless, the higher fitness at the beginning of HFT could not alone explain the decreased $p_e$. This decrease appeared only at the beginning of HFT and not at the end of LFT in which the level of performance was close to the level during HFT. On the other hand, the increase in $t_n$ with HFT could not be attributed to the order of the training sequences. The reverse of the order of the two training phases could eventually enhance the difference in $t_n$ between HFT and LFT.

In contrast to the findings of this study, the previous application of the time-varying model showed an increase in $p_e$ with training for the two studied subjects (6). Furthermore, for both subjects, variations in $p_e$ were correlated with unsteady variations in performance interpreted as a change in the subjects’ adaptability to train (6). This contradiction with the present results could arise from differences in the training program. In the earlier experiment, higher training loads than the ones used in the present study were applied from the beginning, thus yielding a decrease in $p_e$ at the start of the training program. The subsequent increase in $p_e$ partly due to 2 wk of reduced training in the middle of the experiment would also be an adaptation to heavy training. The decrease in exercise adaptation assessed from $p_e$ in the present study would only be temporary and restorable with adequate training. This points out the importance of progressively increasing training load with an adequate period of recovery to prevent staleness (16). Nevertheless, the methodology employed in our previous study could also have obscured the results. The training loads referred to MAP measured every other week and were assumed to vary linearly between two measurements. In contrast with the present study, day-to-day variations in performance were not taken into account, possibly leading to an underestimation of the signal input and thus an overestimation of $p_e$. Nevertheless, because of its potential importance in training periodization, the possible increase in training adaptability with adequate increase in training loads and regeneration periods deserves further investigations.

In conclusion, this study showed that the reduction in recovery time between training sessions yielded a progressive increase in the magnitude and duration of fatigue induced by each bout of training stimulus and also led to a decrease in the resulting adaptations. Reduced adaptation to training loads could arise from lower tolerance to exercise, from higher fitness level, or from a limitation on the body’s capacity to adapt to greater training loads.
REFERENCES


