A Theoretical Study of Taper Characteristics to Optimize Performance

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ABSTRACT
THOMAS, L., and T. BUSSO. A Theoretical Study of Taper Characteristics to Optimize Performance. Med. Sci. Sports Exerc., Vol. 37, No. 9, 1615–1621, 2005. Purpose: The aim of this study was to examine the training factors that could affect taper efficiency. The analysis was done using simulations from a nonlinear model of the training effects on performance giving an individual optimal daily training (ODT) Methods: Training responses were simulated using data from six subjects obtained in a previous training experiment (15-wk program including 3 wk without training). Assuming first a steady state with training equal to ODT, the taper was simulated with various step training reductions up to 100% of previous training. Overload period (OT) was then featured by a 20% step increase in training during 28 d before the taper. Finally, a taper with step reduction was compared with progressive reduction Results: The taper allowed performance gains if training was higher than a minimal level. The best performance without OT preceding the taper was reached with a load reduction of 30.8 ± 11.8% and a duration of 19.3 ± 2.3 d. The best performance with OT preceding the taper was significantly higher than without OT (P < 0.02) and was obtained with a significantly greater load reduction and duration, 39.3 ± 9.9% and 28.0 ± 5.1 d respectively. The best performance with a progressive load reduction was significantly higher than with a step reduction only with OT before the taper (102.2 ± 1.7 vs 101.8 ± 1.5% of performance with ODT, P < 0.005). Conclusion: Greater training volume and/or intensity before the taper would allow higher performance gains, but would demand a greater reduction of the training load over a longer period. The results also pointed out the importance of training adaptations during the taper, in addition to fatigue dissipation. Key Words: RECOVERY, TRAINING SCHEDULE, DETERTRAINING, OVERREACHING, MODELING

The taper is a very sensitive period when the amounts of training load are reduced before a competition. This final period aims to peak performance at a target time. The goal of the taper is to recover from prior heavy training without compromising the previous training adaptations (19,20). Taper efficiency, in terms of performance enhancement, would depend on its own characteristics: duration, rate of reduction of the training load, form of the reduction (step, linear, or exponential) and the balance between volume and intensity of work (20). Kubukeli et al. (14) have suggested that taper efficiency could depend on the features of the training period before the taper as well. All these factors make coaches very insecure in proposing the optimal taper strategy, with only their experience and intuition as tools (20).

Mathematical modeling appeared as a useful and objective tool to analyze how to adjust taper characteristics in order to maximize the performance gains (8,16,17,19). Simulation could provide a convenient technique to determine the optimal combination of reduction in training load and its duration, by means of changing the pattern of training (8,16,17). In the experimental studies, it is difficult to compare a sufficient number of training designs in order to define the best strategy to optimize performance. The initial systems model of the training effects on performance was proposed by Banister et al. (1). The subject was represented by a black box (system) whose response to training was described by a mathematical function called transfer function. This function consisted of the difference between two first-order filters representing two opposite effects: a positive response ascribed to adaptations to training and a negative response ascribed to the exercise-induced fatigue. Banister’s model assumed thus 4 parameters: 2 gain terms, $k_1$ and $k_2$ for positive and negative components respectively, and 2 time constants, $\tau_1$ and $\tau_2$. The knowledge of these parameters allowed an estimation of variation in performance (system output) from training amounts (system input). Mujika et al. (19) attributed gains in performance during the taper to a reduction in the negative influence of training associated with the preservation of the positive influence. Fitz-Clarke et al. (8) described how model derivations could be used to estimate optimal taper duration. The performance response to a training impulse showed that after an initial decrease, performance recovers its initial level after a time noted $t_{d1}$ and reaches afterwards a maximal level after a time noted $t_{d2}$. Optimal taper duration would be comprised between $t_{d1}$ and $t_{d2}$ to recover from previous training and benefit from adaptations (8). Such computations yielded an optimal taper duration between 2 wk ($t_{d0}$) and 4 wk ($t_{d4}$) in a group of national and international level swimmers, which was in keeping with experimental results (19).

Nevertheless, the study of Fitz-Clarke et al. (8) pointed out that Banister’s model assumed that any training $t_n$ days before competition was detrimental for performance. Taking
the model literally would suggest that an athlete should completely stop training during this period, which contradicts with the observations on detraining (25). Another limitation of Banister’s model arose from the comparison of the data of the literature showing that model parameters’ values could be dependent on the severity of the training doses (7). tj values ranged from 1 to 3 d for subjects training four times a week (6) to 23 d for an elite athlete training once or twice a day (5). Using a recursive least squares algorithm showed the magnitude and duration of fatigue produced by a given training dose could increase with the repetition of work bouts (4,7). These observations led to the proposal of a new formulation of Banister’s model, in which fatigue induced by a training dose was assumed to vary with training according to a first order filter (3). This nonlinear model was statistically validated using data from six volunteers participating in a training experiment. The results allowed the demonstration of an inverted-U relationship between daily amounts of training and performance (3). Furthermore, simulations using average model parameters showed a good agreement with actual data in athletes published elsewhere (10). Consequently, the nonlinear model would enable to simulate the response to training more accurately than Banister’s model, in particular in the context of taper after an overload period.

The purpose of this study was thus to utilize this new model to examine the factors that could influence the characteristics of an optimal taper. It was hypothesized that the optimal duration of the taper would not be constant, but would depend on training amounts during both taper and pretaper. Likewise, because insufficient training during the taper was detrimental for performance, it would exist an optimal extent of training reduction, which could depend also on other training features.

**METHODS**

**Mathematical modeling.** The results were obtained from simulations using the model proposed by Busso in 2003 (3). The model is defined by a transfer function where the impulse response to one training dose is $k_1 e^{-\tau_1} - k_2 (e^{-\tau_1} - e^{-\tau_2})$. The gain term for the negative component $k_2$ varies with training doses according to an impulse response, which is $k_3 e^{-\tau_3}$. The relationship between training and performance includes five parameters: two gain terms ($k_1$ and $k_2$) and three decay time constants ($\tau_1$, $\tau_2$, $\tau_3$). The gain term $k_2$ for the negative component is assumed to be a state variable varying over time in accordance with system input. 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, that is, a series of impulse each day, $w$ 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 $w$. $\hat{p}^n$ is thus estimated as follows:

\[
\hat{p}^n = p^* + k_2 \sum_{i=1}^{n} w_i e^{-\tau_1} - \sum_{i=1}^{n} k_3 w_i e^{-\tau_2} \tag{1}
\]

in which the value of $k_2$ at day $i$ is estimated by mathematical recursion using a first-order filter:

\[
k_2^i = k_2 \sum_{j=1}^{i} w_j e^{-\tau_1} - \sum_{j=1}^{i} k_3 w_j e^{-\tau_3} \tag{2}
\]

Simulations were run for the six subjects from their respective model parameters given by Busso in 2003 (3). The mean parameters values were: $k_1 = 0.031 \pm 0.007$ a.u., $k_3 = 0.000035 \pm 0.000010$ a.u., $\tau_1 = 30.8 \pm 1.6$ d, $\tau_2 = 16.8 \pm 3.3$ d, $\tau_3 = 2.3 \pm 1.0$ d, $k_1$, and $k_3$ are expressed in arbitrary units (a.u.), which depended on units for training and performance (4). In this prior study, training sessions consisted of intermittent exercises on a cycle ergometer, and the performance was the average power output developed on an all-out cycle exercise of 5 min. In the present study, training and performance were standardized using the inverted-U shape relationship observed between daily training amounts and the gain in performance (3). This relationship showed that performance would be maximal ($P_{ODT}$) for an optimal daily training (ODT), assuming a long enough training to reach steady state (Fig. 1). A daily training load higher than the optimal level (ODT) would elicit a performance lower than $P_{ODT}$ because of the fatigue induced by oversolicitation (3). The transient decrease in performance despite maintenance of training load corresponds to the definition of the short-term overtraining or over-reaching (9,12,15). In this current study, this period in which the daily training load was higher than ODT was defined as a period of overload training (noted OT). The amounts of training were expressed as a percentage of ODT for each subject. Performance was referred to $P_{ODT}$ so that performance was quantified in a unit (PU) in which $P_{ODT}$ corresponded to 100 PU for each subject, with $p^*$ fixed to 80 PU (Fig. 1). 100 PU was thus the highest level of performance achievable with the same training dose repeated each day. All computations were done from routine written using Scilab© (INRIA-ENPC, France).

**Training simulations.** All simulations began with daily training set to ODT assuming that performance was...
stabilized at 100 PU. The taper period came straight after ODT or after an overload training at 120% ODT during 28 d. As a consequence, simulations without OT assumed two training periods: ODT preceding the taper. With OT, there was three successive training periods: respectively ODT, OT, and the taper. The taper was featured by a step reduction in training, that is, a sudden reduction to a lower level that was maintained thereafter (top of Fig. 2). The extent of training reduction was ranged from 0 to 100% of training previous to the taper. The time allowing to reach the highest performance was assessed for each rate of training reduction. Simulations were also done with progressive taper using linear and exponential training reduction. Linear taper consisted of a linear decrease in training with various speeds of reduction expressed as percentage of ODT per day. Exponential taper consisted of an exponential decrease in training characterized by a constant decay time, noted τ.

Statistics. Means and standard deviations (SD) were calculated for the selected variables. Difference between training situations (with vs without OT or step vs progressive taper) was tested with a paired t-test. The acceptable level of statistical significance was set at P < 0.05.

RESULTS

Figure 2 shows the performance variation over time during a step taper with and without prior OT for one typical subject. Comparison was done using maximal training reduction (100%, i.e., cessation of training), a low reduction of 15% and the reduction eliciting the highest performance gain (31 and 39% without and with OT, respectively, for this subject). With daily training fixed to ODT, performance maintains a level of 100 PU. This is the highest level that could be stabilized with the same training dose repeated each day. With taper, performance increased up to reach a maximal level before decreasing until a steady state. The time to reach maximal performance appeared to differ according with the extent of the load reduction and the pre-taper training.

Figure 3 shows for the same typical subject the maximal performance and the taper duration necessary to reach it according to the extent of training reduction, with and without OT before the taper. Such relationships were obtained for each of the 6 subjects. A minimal percentage of training reduction was observed with OT (11.8 ± 1.5%) so that performance during taper exceeded ODT performance. A maximal percentage was obtained both without and with OT (69.2 ± 19.0 and 69.2 ± 17.6%, respectively). The top of the inverted-U curve of the maximal performance according to the load reduction indicates the existence of optimal values for the duration and the extent of step reduction in training.

The data on the optimal step taper averaged for the six subjects are shown in Figure 4. The characteristics of an optimal step taper without prior OT were a training reduction of 30.8 ± 11.8% over 19.3 ± 2.3 d, whereas optimal values with OT before the taper showed a greater reduction (39.3 ± 9.9%, P < 0.001) over a longer duration (28.0 ± 5.1 d, P < 0.002). Maximal performance reached with optimal taper was significantly greater than P_{ODT} with and without OT before the taper (P < 0.05). The improvement of performance with the taper was greater with than without OT (101.4 ± 1.3 vs 101.8 ± 1.5 PU, P < 0.02). Even though the optimal percentage of reduction was larger with OT, the optimal load during the taper was significantly higher with than without OT (72.8 ± 11.9% of ODT vs 69.17 ± 11.75% of ODT, P < 0.0005). The best performances were reached during the taper with OT, although performance decreased by 2.2 ± 0.7% during OT featured by an increase of training of 20% over 28 d. The computation of the performance gain from the beginning of training reduction (Δ_{Maximal–Pretaper} Performance) enhanced thus the benefit of optimal taper after OT period. This benefit was significantly greater than without OT (P < 0.001). The optimal step taper led to a maximal performance increase of 4.1 ± 2.2 PU, that is, 4.2 ± 2.3% in comparison with the performance at the end of the OT period, whereas subjects...
displayed a maximal performance increase of 1.4 ± 1.3% without OT before the taper.

The optimization of both progressive tapers provided close results in terms of maximal performance and optimal training during the taper. Thus, the comparison between step and progressive tapers focused on the simplest progressive reduction, that is, linear taper. Like with step taper, the best performances reached after a linear reduction were higher with OT than without OT (respectively 102.2 ± 1.7 vs 101.4 ± 1.4 PU; P < 0.005). Between step and linear tapers, there was no statistical difference concerning the optimal taper duration and the maximal performance reached without OT (Fig. 5). With OT before the taper, linear reduction allowed attaining a significant higher performance than a step reduction (P < 0.005). A progressive taper required a longer optimal taper duration after OT (48.5 ± 10.3 d) as well. The duration was reduced to 31 ± 3.4 d if it was only considered the number of days where the load during progressive taper was below 100% ODT. The optimal load reduction after OT, which was 1.4 ± 0.8% ODT per day for linear taper, corresponded to a slow time constant of decay for exponential taper (τ = 81 ± 37 d).

**DISCUSSION**

This model study showed that the optimization of the taper period should reach the best compromise between the extent of training reduction and its duration. The characteristics of an optimal taper period would however depend on prior training. With harder prior training, performance would be maximized with a greater reduction of training for a longer period. Furthermore, a progressive reduction (linear or exponential tapers) in training load would be superior to a sudden reduction (step taper), according to the degree of overload before the taper.

Assumptions in training simulations. One difficulty in simulating the responses to training variations arises from the assumption of the systems model built to analyze training responses. The quantification of systems input aggregated the volume and intensity of exercises done during training session. The resultant amounts of training did not allow to distinguish a possible specific influence of training intensity (18). In other terms, this study dealt with a quantitative view of training rather than with its qualitative aspect. The results obtained by mathematical modeling...
should be examined carefully with respect to data from experimental studies. For most of the authors, performance peaking with training reduction would be successful if reduction concerned mainly the training volume, whereas the intensity was maintained (20,23,26). A review of the literature on taper strategies yielded to conclude that the reduction of total amounts of training should be 60–90% over a period ranging from 4 to 28 d (20). The data of the literature reported in this paper showed however that performance gains have been reported as a result of tapers lasting from 4 to 35 d (20). Because of the large range for the extent of training reduction and the duration, the main question addressed by this study was to examine the factors that could explain such a variability in taper strategies. To analyze the impact of training done before the taper on the characteristics of optimal taper, training simulations were done using the optimal daily training (ODT) arising from nonlinear model. This amount of training would be the theoretical dose that would maximize performance if the same training dose was repeated each day (3). Using 100 and 120% of ODT before training reduction allowed thus comparing the effects of taper for two different levels of previous training.

Another limitation ensues from validation conditions of the nonlinear model, which could be nonrepresentative of real training in athletes. The model and the parameters used in this study came from a controlled experiment in laboratory in which previously untrained subjects had undertaken a high-intensity training program on cycle ergometer (3). It could be difficult to extrapolate these results to all athletic activities and in fitter subjects. Nevertheless, model derivations were compared with data published elsewhere obtained in trained cyclists who doubled their habitual training during 2 wk and then reduced their training during 2 wk (10). The model output in a similar situation was found to adequately fit these experimental data from a more intensive training in athletes (3). Extrapolation of the model could however be limited to such training situations, that is, step variations in an aerobic training over a short period like it was done in the present study. Nevertheless, the application of the nonlinear model to athletes in a real situation would be useful to test the pertinence of the model and to produce parameters more representative of high-level athletes. Furthermore, the model application to a sufficient number of athletes and to various sport activities would be needed to analyze the importance of the interindividual variability and the impact of the type of training (aerobic, anaerobic, resistance, etc.).

Considering the limitations reported above, the model outputs should be compared with data of the literature to check the adequacy of the training design chosen for model simulations. The time to reach maximal performance according to the extent of training load reduction and prior overload were in line with the range of 4–35 d for taper duration observed in experimental studies (20). Only the duration for a slight training reduction after overload was out of this range. Performance improvement without OT before an optimal step taper was around 1.5%. When performance was compared with its level before the taper, performance gains with OT were above 4% with optimal taper. These values are in accordance with the range from 0.5 to 6% given from the data of the literature (20). The arbitrary training according to ODT chosen to simulate responses to the taper appeared thus to provide data comparable to actual responses of athletes. The strength of the analysis in this study was however that the simulations allowed the comparison of the influence of prior training and taper characteristics on its efficiency.

**Optimal characteristics of step taper.** A finding of this theoretical study lies in the variation of the time to reach maximal performance according to other training characteristics. The original model from Banister and coworkers (1) assumed an optimal taper duration whatever prior training. In contrast, the nonlinear model used in this study put on view three main training factors that would influence the time for performance peaking: the extent and the form of training reduction and the pretaper training. A larger training reduction would need a shorter taper to maximize performance. This point is in line with the hypothesis of Kubukeli et al. (14) who proposed to shorten taper period when training volume was highly reduced, in order to limit the loss of adaptations.

The nonlinear model enabled to discern an optimal load reduction, as well as a minimal and a maximal ones to improve ODT performance (Fig. 4). The finding of minimal and maximal reductions of training load to improve performance matches the two main principles of taper formulated by Mujika and Padilla (20): reducing the negative impact of daily training while making performance-enhancing adaptations apparent. The current results are also consistent with experimental research on overtraining and detraining. Maintaining training stimulus at high level may limit recovery, which could lead to a staleness state that would be difficult to reverse (9,13). Conversely, an insufficient training stimulus may cause the loss of training-induced adaptations (11,25). The nonlinear model would give a better description of the responses to training than Banister’s model, because the initial model implied that a complete cessation of training would be the best strategy for tapering (8). This study showed the importance of training loads during the taper, which is in agreement with the recent suggestion by Mujika et al. (21) that further adaptations during the taper would also contribute to performance gains. The only reduction in fatigue without changes in adaptations, as proposed in a prior study by Mujika et al. (19), could be insufficient to reach the best performance during the taper. Indeed, different studies (22,24,26,27) showed that physiologic positive adaptations (metabolic and contractile properties) could occur even during the taper. Therefore, the optimal adjustment of taper features would correspond to the best compromise between the reduction of fatigue and the continuation (and not only the preservation) of positive adaptations as a result of training.

An optimal reduction was also observed from an experimental study in cyclists (22). The results showed that a 50% reduction in training volume was optimal in terms of enhancing performance in comparison with 30 and 80% re-
dutions. The present study provided optimal reduction values slightly lower, 30.8 ± 11.8 and 39.3 ± 9.9%, respectively, without and with OT. These values were lower than the range of 50–90% for reduction in training volume reported from several studies in various sporting activities (20). On the one hand, this difference could be explained by training dose before taper and the characteristics of subjects. Experiments about taper were mainly realized on an athletic population, which would be able to train at harder load levels during OT than a sedentary one. Tapering with a larger training reduction than the one computed in this study could be more beneficial in this case (13). The fact that the optimal reduction was significantly greater with than without OT would be in keeping with this suggestion. On the other hand, the range from 60 to 90% recommended by Mujika and Padilla (20) was deduced from experiments with a short taper, lasting usually less than 15 d. The current results showed that performance could be improved with greater reduction in training than the optimal (up to around 70%), but the taper should be shorter than the optimal duration as well. Therefore, it could be assumed that a short taper lasting less than 15 d would require a training reduction greater than the optimal obtained in this study.

**Optimal characteristics of progressive taper.** No statistical difference in optimal performance was observed between step and progressive tapers without prior OT. Conversely with prior OT, tapering in a progressive manner was significantly more beneficial to performance than a step reduction of training. Only the study by Banister et al. (2) observed a greater improvement in performance with an exponential taper in comparison with a step taper. In this previous study, experimental data were in line with theoretical data from the model proposed by Banister et al. (1). In the present study, an exponential taper yielded a longer duration, about one and a half month with OT before the taper. Nevertheless, because the load was progressively reduced, training load remained above ODT during the first days of the taper after OT (18.0 ± 6.8 d). The first days of progressive tapers could be considered as an overload period. In the total duration of the optimal exponential taper, the number of days with training load below ODT was about 30 d. This duration would be in better accordance with the range of taper durations given in the literature and with the duration of the optimal step taper. The best performance in the present study was produced with a slow reduction of training load. In contrast, Banister et al. (2) obtained the best real performance with a fast decay, τ = 4 d. In addition to the aforementioned factors as the studied population and pretaper training, this difference could arise from the taper lasting 14 d in this previous report, which would require a quicker reduction of training.

**CONCLUSION**

The new formulation of the model allowed a multifactorial analysis of optimal characteristics of the taper (training reduction, duration and form). Optimal taper features would be interdependent and influenced by previous training as well. Greater solicitations before the taper would allow the attainment of the highest performances, but would demand a greater reduction of training over a longer period of time. Moreover, a minimal load would be required to make the taper efficient. This points out the importance of training adaptations during the taper, which should not only act through fatigue dissipation.

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**REFERENCES**


