

A model study of optimal training reduction during pre-event taper in elite swimmers

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Abstract

The aim of this study was to assess responses to taper in elite athletes using computer simulations. Parameters of a non-linear model were derived from training and performance data over two seasons for eight elite swimmers. The fit between modelled and actual performances was statistically significant for each swimmer ($r^2 = 0.56 \pm 0.06$; $P < 0.01$). The simulations were used to estimate characteristics of step and progressive tapers that would maximize performance either (1) after regular training only or (2) after overload training of a 20% step increase in regular training for 28 days. The highest performance with a step taper was greater with than without prior overload training (101.4%, $s = 1.6$ vs. 101.1%, $s = 1.4$ of personal record; $P < 0.01$) but required a longer taper duration (22.4 days, $s = 13.4$ vs. 16.4 days, $s = 10.3$; $P < 0.05$). The optimal progressive taper led to a better performance only after the overload period (101.5%, $s = 1.5$; $P < 0.001$). Negative and positive influences of training were estimated as indicators of fatigue and adaptations to training respectively. During the optimal taper, the negative influence was completely removed, independently of the prior training, whereas the positive influence increased only after overload training. Our computer simulations show that the characteristics of an optimal training reduction in elite athletes depend on the training performed in the weeks prior to a taper.

Keywords: Recovery, over-reaching, training schedule, modelling, detraining

Introduction

A period of reduced training just before a competition with the aim of achieving peak performance at the right moment of the season is termed a “taper” (Mujika & Padilla, 2003). The potential of a taper to improve performance is now well established. A gain in performance of around 3% could be anticipated with a reduction in the training volume of 50–90% over 4–35 days (Mujika & Padilla, 2003). Because of the large range in these recommendations, coaches cannot be certain of the suitability of a tapering strategy for maximizing performance for any given competition. A better knowledge of factors that influence the effectiveness of the taper would be helpful for athletes, coaches, and sports science practitioners and researchers.

The use of a training reduction to maximize performance has been indicated by the modelling of performance variations according to the training

load undertaken over time. This approach, initially proposed by Banister and co-workers (Banister, Calvert, Savage, & Bach, 1975), assumed that performance was the balance between two antagonistic training effects: a positive effect ascribed to adaptations and a negative one ascribed to fatigue. The model incorporates parameters that are constants, unique to individuals, and that ostensibly characterize the response to training of an individual. The model parameters were fitted for each participant from their response to a given training programme. The knowledge of these parameters allowed the computation of fatigue and adaptation indexes over a specified training period. Such an application was used by Mujika *et al.* (1996) to explain taper-induced gains in performance based on the training data of competitive swimmers. Another application was the simulation of changes in performance for variations in training other than that actually undertaken (Fitz-Clarke, Morton, &

Banister, 1991; Morton, 1991; Morton, Fitz-Clarke, & Banister, 1990). This approach identified the optimal duration of the taper (Fitz-Clarke *et al.*, 1991), which should be approximately two to four weeks. A progressive reduction of training can be more effective than a step reduction, a notion in agreement with data observed in triathletes (Banister, Carter, & Zardakas, 1999). The theoretical analysis based on the original model of Banister *et al.* (1975) is possibly flawed because of the underlying linear formulation. The response to a given training dose was independent of the accumulated fatigue with past training. This implies that the duration of the taper should be identical whatever the severity of the training preceding the taper. Moreover, according to the original model, training should be halted completely for the duration of the taper to maximize performance (Fitz-Clarke *et al.*, 1991), which contradicts data on detraining (Neufer, 1989) and tapering (Mujika & Padilla, 2003).

A recursive least-squares algorithm was applied to allow the parameters of Banister's model to vary over time (Busso, Benoit, Bonnefoy, Feasson, & Lacour, 2002; Busso, Denis, Bonnefoy, Geysant, & Lacour, 1997). These initial studies showed that responses to a single training session could vary according to the difficulty of the previous sessions. This led us to propose a formulation of a new non-linear model. This non-linear model implied that the magnitude and duration of the fatigue produced by a given training dose increased with the repetition of exercise bouts, and was reversed when training was reduced (Busso, 2003). Therefore, the restoration of the tolerance to training could contribute to the peak in performance induced by the taper (Mujika, Padilla, Pyne, & Busso, 2004). The non-linear model was validated using data from six previously untrained participants who volunteered to train on a cycle ergometer (Busso, 2003). The model outputs were used to analyse the factors that influence the optimal taper characteristics – the duration, extent, and form of the training reduction (Thomas & Busso, 2005). This theoretical study was based on simulations of the responses of the six participants of the study of Busso (2003) to various tapering strategies. Greater solicitations before the taper facilitated better performances, but presumably would demand a greater reduction of the training loads over a longer period. Moreover, an optimal progressive reduction in training led to a better performance than an optimal step reduction when the taper was preceded by an overload period. It is possible that the benefits of the taper could result from additional gains in adaptations and not only from fatigue dissipation. This scenario would be in line with studies that have shown that additional positive physiological adaptations during the taper contributed to the enhanced performance (Neary,

Martin, & Quinney, 2003b; Neary, Martin, Reid, Burnham, & Quinney, 1992; Shepley *et al.*, 1992; Trappe, Costill, & Thomas, 2001).

Nevertheless, the characteristics of the optimal modelled taper were not a good match to the data reported in the literature (Mujika & Padilla, 2003), in particular the mean values of the optimal training reduction, which were less than 40%. These discrepancies may have arisen from the data used to derive the model, which were sourced from a non-athletic population enrolled in a controlled experiment, in contrast with most studies on the taper, which have focused on athletes. Therefore, the results of that theoretical study deserve to be re-examined using model parameters obtained with athletes in a real training context (Busso & Thomas, 2006).

The aim of the current study was to apply a non-linear model with elite swimmers under real training conditions to determine the influence of pre-taper training on the characteristics (duration, extent, and form of the training reduction) and effectiveness (performance gain) of the optimal taper in an athletic population. In the first part of this investigation, we applied the non-linear model to describe the athletes' response to their training. The model parameters fitted in these swimmers were then used for computer simulations to re-examine the characteristics of the optimal taper according to prior training. Finally, we determined whether the gain in performance with an optimal reduction of training resulted from further adaptations in addition to fatigue dissipation.

Methods

Training and performance data

The data used in this paper were captured over two complete seasons of four female and four male national and international swimmers who specialized in 100-m and 200-m events. The data from the first season were extracted from a larger group of 18 swimmers studied previously (Mujika *et al.*, 1995, 1996). In the present study, only the swimmers with complete training and performance data logs over two successive seasons were selected. Their mean age and competition experience were 19.8 years ($s=2.5$) and 12.9 years ($s=3.0$), respectively. Written informed consent was obtained from the participants before entering the study. The swimmers followed the training programme prescribed by their team coaches: the authors of the present study had no involvement in this process. The mean number of measured performances during the two seasons was 32.0 ($s=3.8$). Performance was expressed as a percentage of the personal record achieved by each swimmer during the season

preceding the study. Their personal record gave a mean international point score (IPS) for the eight swimmers of 885 ($s=21$) (see <http://www.swimnews.com/Ranking.html>). Three swimmers had a score higher than 900, a benchmark criterion for swimmers of international calibre (Pyne, Lee, & Swanwick, 2001).

Assessment of the training load accounted for the training volume and intensity for workouts in the water, and the dryland workout times. These three training parameters were recorded each day for each swimmer and reported as that swimmer's mean training per week. The training volume was quantified as the distance swum in kilometres. The training intensity was determined from the swimming speed of each exercise. Intensity was divided into five domains relating to the relationship between blood lactate concentration and swimming speed. This relationship was established individually after lactate testing as described by Mujika *et al.* (1995). Intensities I, II, and III corresponded to swimming speeds less than ($\approx 2 \text{ mmol}\cdot\text{l}^{-1}$), equal to ($\approx 4 \text{ mmol}\cdot\text{l}^{-1}$), and slightly above ($\approx 6 \text{ mmol}\cdot\text{l}^{-1}$) the speed at the blood lactate accumulation threshold, respectively. Intensity IV represented swimming speeds eliciting high lactate concentrations ($\approx 10 \text{ mmol}\cdot\text{l}^{-1}$). Maximal-intensity sprint swimming was defined as intensity V. The corresponding lactate concentration for intensity V was estimated as $16 \text{ mmol}\cdot\text{l}^{-1}$. Blood lactate testing was repeated at regular time intervals throughout the follow-up period, and the adequacy of the individual relationship between blood lactate and swimming speed was tested repeatedly during training. The target blood lactate concentrations during the different training sets were divided by two for use as simple weighting coefficients for training intensity. Training load for training in the water was thus calculated as the sum of the

distances covered at intensities I, II, III, IV, and V multiplied by the weighting coefficients 1, 2, 3, 5, and 8, respectively. Dryland training was initially recorded in minutes. To quantify the training load due to the dryland training sessions in the same training units as the workouts in the water, coaches and swimmers empirically estimated that 1 h of dryland training was equivalent to 1 km swum at intensity I, 0.5 km at intensity IV, and 0.5 km at intensity V. In other terms, 1 h of dryland training corresponded to a training load equal to $1 \times 1 + 5 \times 0.5 + 8 \times 0.5 = 7.5$ arbitrary units.

The mean weekly training load (MWTL) was computed as follows:

$$\text{MWTL} = 1 \times \text{kmI} + 2 \times \text{kmII} + 3 \times \text{kmIII} + 5 \times \text{kmIV} + 8 \times \text{kmV} + 7.5H$$

where kmI, kmII, kmIII, kmIV, and kmV are the mean distances per week covered at intensities I, II, III, IV, and V, respectively, and H is the number of dryland training hours per week. The weekly variations in the total training load for the entire group of swimmers are shown in Figure 1.

Modelling of the responses to training

The model proposed by Busso (2003) was applied to describe the relationship between training load and performance over time. This model defines performance $p(t)$ as the balance between the positive and negative responses to training, termed "adaptation" and "fatigue" respectively. The extension from earlier model formulations is that an intensification of training is assumed to result in greater fatigue during a single session, which will require a longer period of recovery. Briefly, a quantity of training $w(t)$ produces a proportional amount of adaptation and

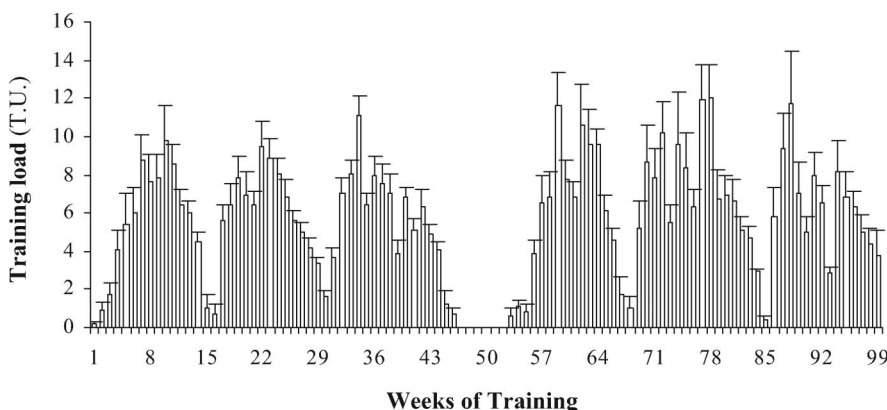


Figure 1. Mean daily training load each week for the entire group of swimmers during the two training seasons (means $\pm s_x$). T.U. = training unit.

fatigue given by the weighting factors (gain terms) k_1 and k_2 respectively. These amounts add to previous levels and then decay exponentially until a new training session provokes modifications. The rates of decay of adaptation and fatigue are dependent on their respective time constants τ_1 and τ_2 . Contrary to the original model of Banister *et al.* (1975), in which all the model parameters were time invariant, here the gain term for the negative component varies with training – that is, after a session, k_2 increases by an amount proportional to the quantity of training and then decays exponentially from this new value. The variation in k_2 immediately after the session is related to the quantity of training weighted by the gain term k_3 , and the decay rate is determined by the time constant τ_3 .

Mathematically, the model is based on a transfer function that comprises two antagonistic first-order filters representing the positive and negative training effects on performance. The transfer function is characterized by an impulse response to one training dose as follows: $k_1 \cdot e^{-t/\tau_1} - k_2(t) \cdot e^{-t/\tau_2}$. The gain term for the negative component k_2 varies with training doses according to an impulse response: $k_3 \cdot e^{-t/\tau_3}$. Performance $p(t)$ is estimated by the convolution product of the training doses $w(t)$ with the impulse response added to the basic level of performance p^* . $w(t)$ is considered to be a discrete function – that is, a series of impulses 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 . The performance level \hat{p}^n is thus estimated as:

$$\hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w_i e^{-(n-i)/\tau_1} - \sum_{i=1}^{n-1} k_2^i w_i e^{-(n-i)/\tau_2}$$

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

$$k_2^i = k_3 \sum_{j=1}^i w_j e^{-(i-j)/\tau_3}$$

The modelled training response depends on five parameters: two gain terms (k_1 and k_3) and three decay time constants (τ_1 , τ_2 , τ_3). The gain term k_2 for the negative component is assumed to be variable over time in accordance with training doses. The gain terms are expressed in arbitrary units, which depend on units for training and performance, and the decay time constants are expressed in days. The five parameters were individually determined by fitting the modelled performances to the actual performances by the least square method, which

minimizes the residual sum of squares (RSS) between them:

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

where n takes the N values corresponding to the days of measurement of the actual performances.

Adaptations and fatigue were estimated as the positive and the negative influences of training on performance, computed from the combined effects of both model functions on performance (Busso Candau, & Lacour, 1994). The amount of training on day i had an effect on performance on day n quantified by

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

The values of the positive and negative influences on day n (PI^n and NI^n respectively) were estimated from the sum of influences of each past training amount depending on whether the result was positive or negative:

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

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

Model performance on day n was thus the difference between PI^n and NI^n . In the current study, the positive and negative influences of training on performance were estimated for both actual training and computer simulations.

Training simulations

Simulations were run for the eight participants from their respective model parameters fitted from their responses to actual training. For each participant, all simulations began with daily training set to the mean training load of the 40 weeks with the highest training loads over the two seasons (regular training). This first training period was assumed to be long enough to stabilize performance. Without overload training, a taper period occurred immediately after regular training. With overload training, an overload period at 120% of regular training for 28 days occurred immediately before the taper. As a consequence, simulations without overload training assumed two consecutive training periods: regular training and taper. With overload, there were three successive training periods: regular training, overload training, and taper. The taper was seen as a step reduction in training – that is, a sudden reduction to a lower

training load that was maintained thereafter. The extent of training reduction ranged from 0 to 100% of the training before taper (regular or overload training). The time required to reach the highest performance was assessed for each rate of training reduction. Simulations were also done with progressive tapers using both linear and exponential training reductions. The linear taper consisted of a linear decrease in training. The exponential taper consisted of an exponential decrease in training characterized by a constant decay time noted τ . All computations were performed with a routine written using Scilab© (INRIA-ENPC, France).

Statistics

Means, standard deviations (s), and standard errors (s_x) were calculated for the selected variables. The statistical significance of the model fit was tested for each participant by analysis of variance (ANOVA) of the residual sum of squares. The coefficient of determination (r^2) was computed as an indicator of goodness-of-fit. The normality of the residual error was tested for each participant using the Shapiro-Wilk test. The effect of sex was evaluated for all the studied variables using an unpaired t -test. As no significant difference between the sexes was observed, the data for males and females were combined. To assess the effects of the training before taper, the characteristics of the optimal simulated taper according to prior training (without or with overload) were compared using a paired t -test. To examine the effects of the form of training reduction (i.e. step, linear or exponential), the characteristics were compared using one-factor ANOVA and Scheffé’s procedure as the *post-hoc* test. Performance, negative and positive influences of training before and after the optimal taper according to prior training were compared using two-way (2×2) repeated-measures factorial ANOVA with the Bonferroni procedure as the *post-hoc* test. The effects of the taper on negative influence were tested using a one-group test because the post-taper negative influence value was zero for each participant regardless of the simulated training before the optimal taper. Statistical significance was set at $P < 0.05$.

Results

Model fitting to actual data

The modelled performances showed a significant fit with the actual performances over the two seasons for the eight swimmers ($P < 0.01$). The r^2 -values were 0.56 ($s = 0.06$; range 0.45–0.63) with $P < 0.01$ for three participants and $P < 0.001$ for the other five participants. The mean estimates of the model parameters are shown in Table I. The hypothesis of a normal distribution for residuals was rejected in only one participant.

The individual model parameters allowed the analysis of the real training undertaken by the eight swimmers by estimating the variations of the positive and negative influences of training on performance during the two seasons. Figure 2 shows box plots of the respective distribution (median, quartile, range) of the training load and the positive and negative influences for each swimmer over each of the two seasons. These performances are given in Table II. The position of the black dots in Figure 2 reveals that the swimmers achieved their best performances when the training load was reduced, and when the negative influence was low and the positive influence was high. Figure 3 illustrates the results of the application of the mathematical model for one participant. The response to training of this swimmer was representative of the whole group, since, as indicated by the vertical dotted lines, he achieved his best performances after a taper period when the negative influence was reduced and the positive influence was elevated.

Computer simulations

All simulated training began with regular training set to 9.36 training units ($s = 2.83$), stabilizing performance at 99.1% ($s = 2.3$) of each individual’s personal record. During overload training, the performance decreased significantly by 1.2% ($s = 1.0$) ($P < 0.01$) before the training reduction.

The characteristics of the optimal taper with a step reduction in training are shown in Figure 4. The optimal taper without prior overload training included a reduction in training of 65.3% ($s = 30.5$) over 16.4 days ($s = 10.3$). After overload training, the

Table I. Parameter estimates (mean \pm s).

k_1 (arbitrary units)	k_3 (arbitrary units)	τ_1 (days)	τ_2 (days)	τ_3 (days)
0.0315 \pm 0.0117	0.0040 \pm 0.0035	45.6 \pm 12.7	11.3 \pm 7.9	3.8 \pm 1.8

Note: k_1 , multiplying factor for the positive model component; k_3 , multiplying factor for k_2 , which is the multiplying factor for the negative model component; τ_1 , time constant of decay for the positive model component; τ_2 , time constant of decay for the negative model component; τ_3 , time constant of decay for k_2 .

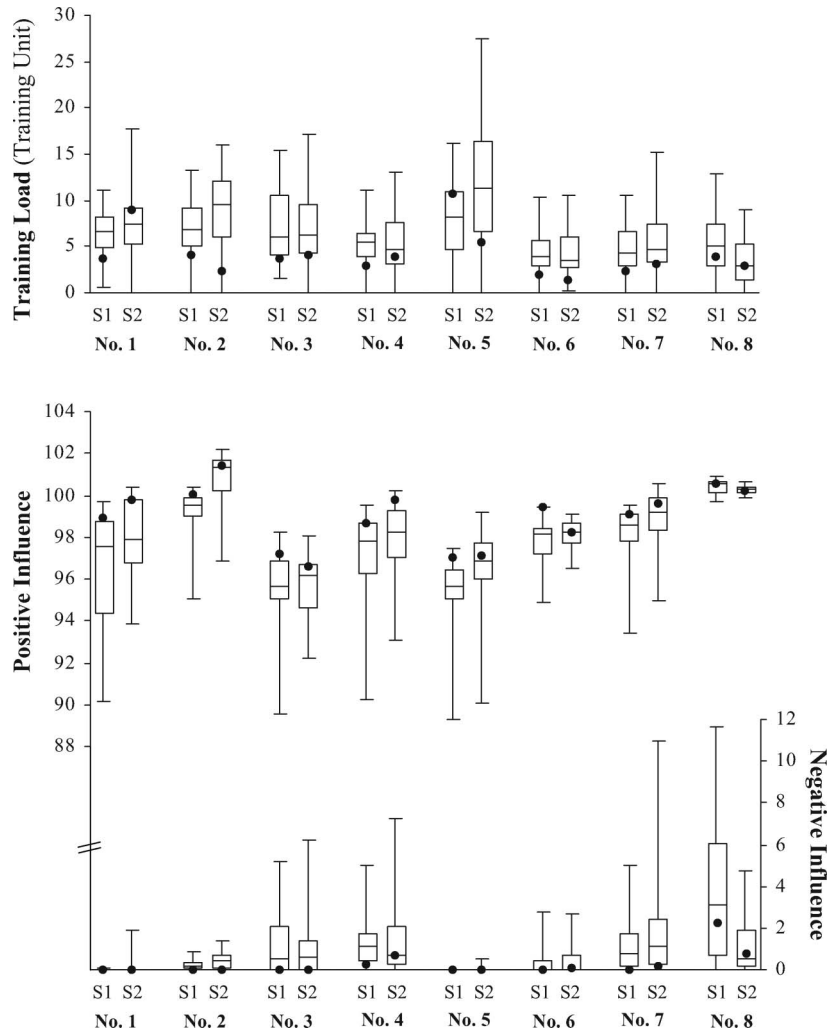


Figure 2. Spread (median, quartile, range) of the training load, and the positive and negative influences of training for each swimmer (No. 1 to No. 8) over season one (S1) and season two (S2). The black dots indicate the level of these parameters when the swimmer achieved his or her best performance in each of the two seasons. The positive and negative influences are expressed in the same units as that used for performance.

Table II. Best performance as a percentage of previous personal record for each swimmer during each studied season.

	Female swimmers (<i>n</i> = 4)				Male swimmers (<i>n</i> = 4)			
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Season 1	100.59	102.05	99.27	98.91	98.94	100.28	100.37	99.86
Season 2	100.76	102.23	99.21	101.61	98.52	99.76	102.94	102.16

Note: A performance over 100% corresponds to an improvement in the swimmer’s personal record.

extent of the optimal reduction was not significantly different (67.4%, *s* = 27.0) but had to be maintained over a longer period (22.4 days, *s* = 13; *P* < 0.05). The absolute training load during the optimal taper was higher with than without prior overload training (4.1, *s* = 4.6 vs. 3.6, *s* = 4.3 training units; *P* < 0.05). The maximal performance reached with the optimal step taper was significantly greater with than without a prior overload period (101.4%,

s = 1.6 vs. 101.1%, *s* = 1.4 of personal record; *P* < 0.01). In both cases, maximal performance was significantly greater than that with regular training. The comparison from the beginning of the taper showed that the performance gain during the step taper after overload training (3.60%, *s* = 2.58 of personal record) was significantly greater than without prior overload (1.99%, *s* = 1.64 of personal record; *P* < 0.01).

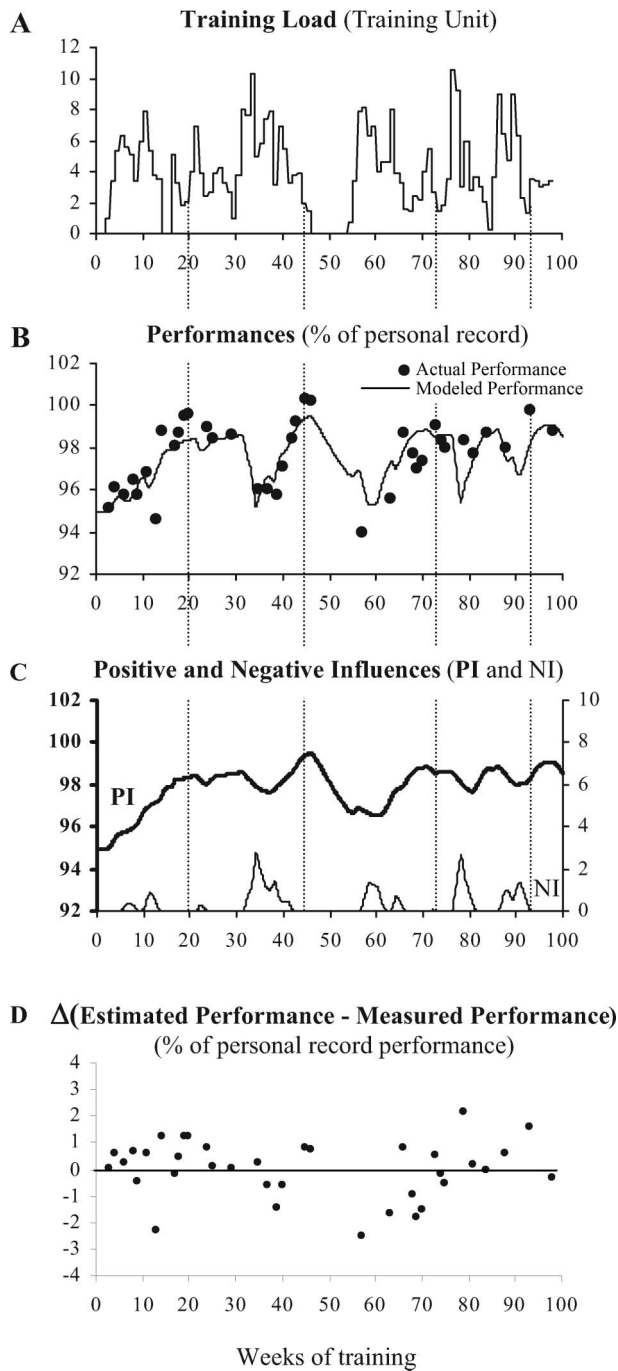


Figure 3. Application of the model to swimmer No. 6. (A) Mean daily amount of training by week. (B) Fit between modelled and actual performance. (C) Profiles of positive and negative influences of training on performance (PI and NI respectively). PI and NI are expressed in the same units as that used for performance. T.U.=training unit. The vertical dotted lines showed the respective levels of training, PI and NI when the swimmer achieved his best performances. (D) The residual difference between actual and estimated performance over time.

The characteristics of the optimal taper according to the form of training reduction are shown in Table III. Both with and without overload training before taper, the two forms of progressive taper

(i.e. linear and exponential) required a training reduction significantly less, over a longer duration, than the step taper. Without overload before taper, no statistical difference was observed for the taper-induced performance gains between the three forms of training reductions. When the taper followed overload training, the highest performance attained with the two progressive tapers was significantly better than with the step taper ($P < 0.001$).

Variations in performance and the positive and negative influences of the training with the optimal step training reduction are shown in Figure 5. Before the taper, the negative influence was significantly greater with than without overload training (2.9, $s = 2.5$ vs. 1.7, $s = 1.6$ arbitrary units; $P > 0.05$), whereas no statistical difference was observed for the pre-taper positive influence. The pre-taper performance was significantly lower with than without overload training. The post-taper performance was significantly greater with prior overload training, given that the negative influence was completely removed with the optimal taper, independently of the prior training, whereas the positive influence increased significantly only during taper following overload training (from 100.9%, $s = 1.8$ to 101.4%, $s = 1.6$; $P < 0.05$).

Discussion

The present study estimated model parameters for competitive swimmers in real training conditions. The model simulations using these parameters confirmed that pre-taper training influences the characteristics and effectiveness of the optimal taper. A greater overload before the taper leads to higher performances, but requires a longer taper. A progressive training reduction is preferred over a step reduction to enhance performance. The gain in performance was essentially explained by the dissipation of the negative influence of training. The taper can also be of benefit through a small gain in the positive influence only in the case of an overload before a reduction in training.

Model parameters obtained from actual training

The obtained model parameters allowed us to carry out a theoretical analysis of the taper more representative of athletes than in our previous study (Thomas & Busso, 2005). That work was conducted using data from a controlled experiment in non-athletes, which provided useful data to test experimental models (Busso, 2003). Nevertheless, the artificial situation and the participants' fitness might have produced model outputs not fully representative of athletes' responses to training (Busso & Thomas, 2006). To extend that earlier work, the

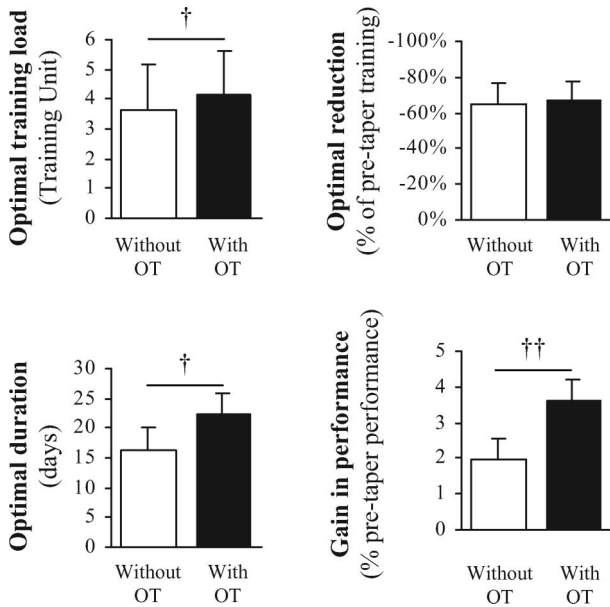


Figure 4. Effect of the pre-taper training on the characteristics of the optimal step taper (means \pm s.e.). Significant difference between taper without and with a prior overload period (OT): † $P < 0.05$, †† $P < 0.01$.

Table III. Estimated characteristics of the optimal simulated taper without and with prior overload training (OT) according to the form of the training reduction (mean \pm s).

	Form of training reduction during taper		
	Step	Linear	Exponential
Mean reduction (%)			
Without OT	65.3 \pm 30.5	46.3 \pm 25.5*	54.7 \pm 31.4*#
With OT	67.4 \pm 27.0	43.1 \pm 20.7*	51.6 \pm 27.5*#
Duration (days)			
Without OT	16.4 \pm 10.3	25.4 \pm 17.4*	22.3 \pm 14.8*
With OT	22.4 \pm 13.4	42.5 \pm 29.8*	39.1 \pm 31.0*
Highest performance (% of personal record)			
Without OT	101.1 \pm 1.4	101.1 \pm 1.4	101.1 \pm 1.4
With OT	101.4 \pm 1.6	101.5 \pm 1.5*	101.5 \pm 1.5*

Note: Statistically different from step taper: * $P < 0.05$. Statistically different from linear taper: # $P < 0.05$.

non-linear model was applied to athletes in real training conditions in the present study. To have a sufficient number of participants with a homogeneous training level, we had to use data from both male and female swimmers.

The application of the non-linear model proposed by Busso (2003) allowed a satisfactory description of the performance variations during the two seasons studied in the eight elite swimmers. The goodness-of-fit between modelled and actual performances showed r^2 -values close to those obtained with the original model (Banister *et al.*, 1975) in similar circumstances, for example $r^2 = 0.65$ ($s = 0.12$) in 18 elite swimmers during one competitive season (Mujika *et al.*, 1996). Although the distribution of

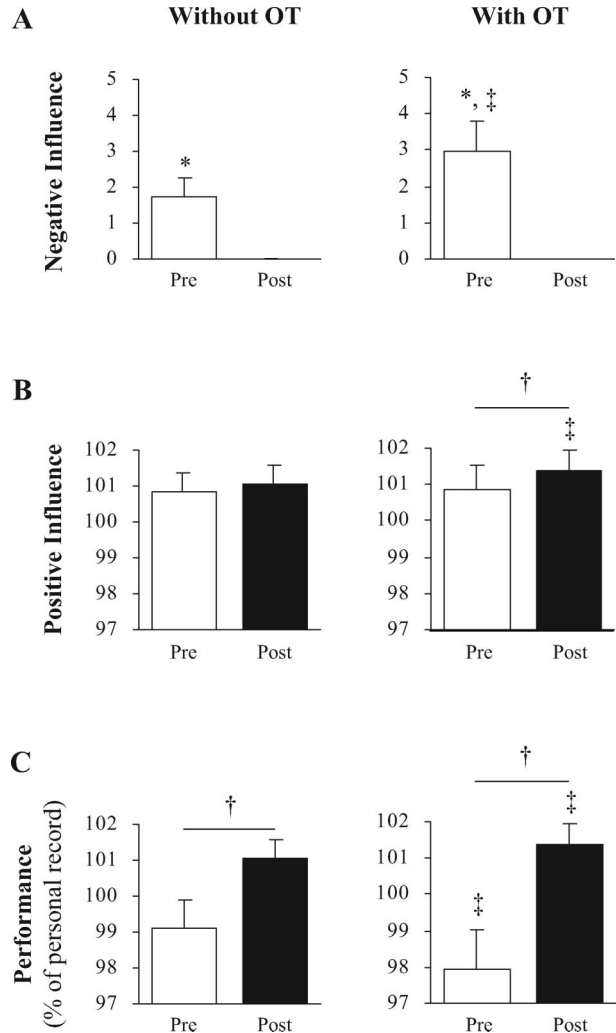


Figure 5. Effects of the optimal step taper without and with prior overload training (OT) on the negative (A) and positive influences (B) and on performance (C). The negative and positive influences are expressed in the same units as that used for performance (mean \pm s.e.). Statistically different ($P < 0.05$): *from 0 (for NI); †between pre-taper (Pre) and post-taper (Post); and ††between values without and with overload training.

the residual values was generally normal, large differences between actual and modelled performances were observed. The model appeared to underestimate some of the better individual performances and overestimate the poorer performances. The goodness-of-fit in these highly trained participants in real training conditions was poorer than that obtained with data from less fit participants in controlled laboratory training (Busso, 2003). Such an experiment had the advantage of allowing a frequent evaluation of performance using a reproducible test and a precise quantification of the changes in the amounts of training. This precision in the data collection could explain the high accuracy of the performance fitting in this earlier study (Busso, 2003). Conversely, the training undertaken by the swimmers in the present study was

complex and even the quantification of six water and dryland training variables would not be sufficient to account for the multiple components of training (Mujika *et al.*, 1996). Furthermore, the actual performances used in this study were not measured in the same conditions (different pool, importance of the competition), which could hamper the quality of the relationship between training load and performance.

Other extensions of the original model, such as variations in k_1 , could be considered. The precision of the data would, however, limit the application of more complex models to describe the variations in performance with training. Our approach using laboratory experiments in non-athletes to test the model, associated with an observational study to derive its parameters, could help to evaluate new refinements of the model.

Computer simulations and optimal taper

Individual responses to training were simulated for two training situations: with or without an overload period before the taper. The overload, or more precisely the unaccustomed training, was evaluated from a 20% increase in workloads from actual mean training assessed from the 40 weeks with the highest training loads. This choice was supported by the obtained gain in performance during the taper, which was well within the range reported in the literature (Mujika & Padilla, 2003).

The theoretical characteristics of the optimal taper matched the data from the literature, which suggests a training reduction of 50–90% over 4–35 days (Mujika & Padilla, 2003). Contrary to our previous report (Thomas & Busso, 2005), greater solicitations before the taper would not require a significantly greater relative reduction of training during the taper. The optimal rate of training reduction ranged from about 45% to 70% depending on the form of the reduction. Competitive cyclists obtained a greater gain in performance during a 7-day progressive taper with a 50% reduction in training volume than with 30% and 80% reductions (Neary, Bhambhani, & McKenzie, 2003a). Unfortunately, modelled responses to changes in the amount of training cannot distinguish the specific influence of the volume and intensity of training. The quantification of training, required for the modelling procedure, has to aggregate several training variables into a single variable, which does not allow the differentiation of their respective effects on performance (Taha & Thomas, 2003). It is generally recognized that performance will peak with a decrease in training if the volume of training is reduced, whereas the average intensity should be maintained (Mujika & Padilla, 2003; Neary *et al.*, 2003a; Shepley *et al.*, 1992).

The results of the present study show substantial inter-individual variability in the characteristics of the optimal taper. These large inter-individual differences could be partially attributed to a lack of precision of the model, but also variability in the physical and/or psychological responses to training (Mujika *et al.*, 1996). This finding highlights the importance of the individualization of the taper programme. Compared with previous theoretical results with model parameters in non-athletes (Thomas & Busso, 2005), the present results indicate that the characteristics of the optimal taper also depend on the level of previous training. Highly trained athletes need a greater reduction of training over a slightly shorter period than less trained individuals.

The characteristics and the effectiveness of the optimal taper are also influenced by previous training. A 20% increase in training during 28 days requires a higher training load during the taper over a longer duration, and a progressive reduction in training elicits better results than a step reduction. A progressive taper requires a smaller reduction in training over a longer period than a step taper whatever the pre-taper training. In our previous study, substantial differences between progressive and step tapers were observed only when an overload preceded the taper (Thomas & Busso, 2005). In this respect, it is worth noting that some individual performances during the follow-up seasons were slower than the swimmers' personal records. Although this is not unusual in highly trained athletes, it is also possible that the training programme followed by these swimmers could be modified to improve performance.

The impact of the pre-taper training on the duration of the optimal taper is clear in terms of reduced fatigue. Overload training causes a greater stress, which requires a longer period to recover. Nevertheless, this impact could be also explained by the adaptations to training, since higher training loads could result in adaptations peaking at a higher level but taking longer to produce. Thus, another goal of this study relied on the computation of the positive and negative influences of training on performance, as indicators of the adaptations and the fatigue respectively (Busso *et al.*, 1994). The further gains in the positive influence during the optimal modelled taper preceded by an overload period suggest that the gains in adaptations and in performance during the taper are determined by the training preceding this final period. Even though the gains in performance during the taper are essentially explained by the reduction in fatigue, an increase in the adaptations during the taper was obtained when it was preceded by an overload period. This combination of responses confirmed our recent suggestions that further adaptations during the taper could

contribute to performance enhancement (Mujika et al., 2004; Thomas & Busso, 2005). This scenario is in line with the experimental results of different studies showing that physiological adaptations (metabolic and muscle contractile properties) could occur even during the taper (Neary et al., 1992, 2003b; Shepley et al., 1992; Trappe et al., 2001).

Conclusion

The parameters of the non-linear model with competitive swimmers in real training conditions allowed a theoretical analysis of the characteristics and effectiveness of the optimal taper that is more representative of high-level athletes than previous studies. The taper should be individualized, embracing the knowledge that the form of training reduction and the level of training before the taper are key factors. The computer simulations showed that an overload period before the taper is essential to maximize performance, but imposes specific requirements during the taper period. A 20% increase in normal training during 28 days before the taper requires a step reduction in training of around 65% over 3 weeks, instead of 2 weeks when no overload training is performed. A progressive (linear or exponential) taper is preferable after prior overload training, but it should last nearly twice as long as the step taper. Although the taper essentially acted through fatigue dissipation, the variations in positive and negative influences of training showed that the benefit of a prior overload period results from further adaptations that occur during the taper period. These findings also confirm the relevance of the original modelling approach in the study of individual responses to training and the optimization of tapering strategies.

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