Eur J Appl Physiol (1999) 79: 182–191

ORIGINAL ARTICLE

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Training theory and taper: validation in triathlon athletes

Accepted: 1 September 1998

Abstract This paper defines a training theory with which to predict the effectiveness of various formats of taper in optimizing physical performance from a standardized period of training and taper. Four different taper profiles: step reduction vs exponential (exp) decay and fast vs slow exp decay tapers, were simulated in a systems model to predict performance p(t) resulting from a standard square-wave quantity of training for 28 days. The relative effectiveness of each of the profiles in producing optimal physical improvement above pre-taper criterion physical test standards (running and cycle ergometry) was determined. Simulation showed that an exp taper was better than a step-reduction taper, and a fast exp decay taper was superior to a slow exp decay taper. The results of the simulation were tested experimentally in field trials to assess the correspondence between simulation and real-training criterion physical tests in triathlon athletes. The results showed that the exp taper ($\tau = 5$ days) group made a significantly greater improvement above a pre-taper standard ($P \leq 0.05$) than the step-reduction taper group in cycle ergometry, and was better, but not significantly so, in a 5-km run. A fast exp taper group B ($\tau = 4$ days) performed significantly better ($P \leq 0.05$) in maximal, cycle ergometry above a pre-taper training standard than a slow exp taper group A ($\tau = 8$ days) and was improved more, but not significantly so, than group A in a 5-km criterion run. The mean improvement on both physical tests by exp decay taper groups all increased significantly ($P \leq 0.05$) above their pre-taper training standard. Maximum oxygen uptake increased significantly in a group of eight remaining athletes during 2 weeks of final taper after three athletes left early for final preparations at the race site.

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Key words Training theory · Modeling · Taper · Performance

Introduction

Taper is an effective way to ensure recovery from heavy training and is generally accepted as an integral part of optimal preparation for competition (Coyle et al. 1984; Gibla et al. 1994; Houmard and Johns 1994; Houmard et al. 1994; Johns et al. 1992; Neufer et al. 1987). Recent experimental evidence supports the beneficial physical and physiological effects of taper (Houmard et al. 1994; Shepley et al. 1992). However, the specific form and size of the training impulse, the length of its time course and the onset time, time course and format of taper have not been well defined or standardized.

Taper is characterized as a special period during which the training stimulus is reduced in a systematic, non-linear fashion (Houmard et al. 1994). Recent evidence has demonstrated that much of the performance decrement and loss of physiological adaptation that inevitably accompanies extensive detraining (Hickson et al. 1982, 1985; Houmard et al. 1990b) may be minimized if training is either maintained at a reduced level (Gibla et al. 1994; Houmard and Johns 1994; Johns et al. 1992; Neufer et al. 1987) or tapered (Houmard and Johns 1994; Houmard et al. 1994; Johns et al. 1992; Neufer 1989).

An advantage in the physical performance resulting from the use of a taper protocol compared with a step reduction in training volume prior to competition has also become apparent. In one study a 70% reduction of normal training volume for 3 weeks did not significantly improve a 5-km run time or muscular power in distance runners (Houmard et al. 1990a). In contrast, a 7-day taper with an overall 85% reduction in weekly training volume improved both a 5-km race time and muscular power (Houmard et al. 1994). These results indicate that when training volume is reduced progressively and rapidly to an extremely low level, physical performance is improved more than by a single, or several step reductions of up to 2/3 the training volume during a more extended period. The latter method appears only to maintain an existing performance capability (Houmard et al. 1990a).

Although it is well known that maximum oxygen consumption ($\dot{V}O_{2\,max}$) increases with training in the relatively untrained, recent studies of taper have demonstrated an improvement in physical performance without an increase in $\dot{V}O_{2\,max}$ in those already well trained (Houmard et al. 1994; Neufer et al. 1987). Improvement in physical performance has been attributed to adaptation at the muscle level, where some improved strength and recovery from the fatigue of heavy training, rather than an improvement in $\dot{V}O_{2\,max}$ has been considered the determining factor. However, if an imposed physical training stimulus is of sufficient intensity and duration to cause adaptation, producing a higher level of physical work than previously attainable prior to training, it seems axiomatic that both muscular and aerobic power should improve. This and other inconsistencies described in training studies to date: why running performance improves concomitantly with a decreased $\dot{V}O_{2\,max}$ and reduced training (Houmard 1991); why physiological and biochemical adaptation, gained during rigorous training, decay steeply as physical performance increases during reduced training (Coyle et al. 1984, 1985, 1986; Hickson et al. 1985; Houmard et al. 1994), may stem from the lack of underlying theory to explain, and established standard methods to investigate, training phenomena quantitatively. Standard methodology should include measurement of:

1. The dose of exercise undertaken in a given period (implicit in the type, pattern, frequency, duration and intensity of effort in a standard period, (per session, day or week).
2. The format of training, e.g. impulse (pulse width), step (step size), ramp (ramp slope), or pseudo-random binary number (number and size designation).
3. The extent and format of taper, step reduction (negative step size), ramp (negative ramp slope), and exp decay (size of the decay time constant).

Banister et al. (1996) have defined a quantitative theoretical approach to producing predictable physical, physiological and clinical responses to a defined quantity and format of training followed by taper. In the present study the physical and physiological response of a group of triathletes to four patterns of taper from a standardized block of training has been predicted in a simulation study, based upon theory. The results of the simulation have been subsequently compared with the real result of preparing athletes for competition along the different preparatory paths of the simulation study.

Training theory

The training theory proposed is that a precisely measured quantity of training, above that currently being practiced, followed by an appropriate taper, will improve physical, physiological and biochemical test indices of the trainee above both a baseline pre-training level and a pre-taper training level by a determined amount which may be predicted. The quantity of daily training effecting this result, termed the training impulse (TRIMP), may be calculated from the duration and intensity of exercise and expressed quantitatively. This latter quantity determines the level of stimulus an individual absorbs to activate the genetic expression of resources necessary for the organism's needs if it is to adapt to routinely producing the new increased daily level of energy expenditure required, without breakdown. A systems model of training (Fig. 1) from Banister and Fitz-Clarke (1993) shows diagramatically the basic process of predicting performance p(t) from training by transforming a daily TRIMP score [w(t)] into separate daily scores of hypothesized fitness [g(t)] and fatigue [h(t)]. The difference between g(t) and h(t), measured in arbitrary units (AUs) of the TRIMP, at any point in time should trace a predicted time course p(t) for a real physical performance. p(t), therefore, may be iteratively modeled to match the time course of real, serially measured, physical criterion performances, e.g. running or ergometry tests either measured in points, normalized to an existing world record arbitrarily set at 1000 points, or in conventional units of the type of test (seconds or Watts). TRIMP data, the signal quantitative measure of the amount of training undertaken, is manipulated in systems modeling of training from the parameter vector of the model that consists of two multiplying factors k_1 and k_2 which convert the TRIMP measurement [w(t)] to respective fitness and fatigue impulses, and two decay time constants τ_1 and τ_2 that define the relative decline of accumulated fitness and fatigue, at different rates, in the interval between training sessions and during any taper prior to competition. Default parameters of the model parameter vector have been determined, validated and rationalized previously (Fitz-Clarke et al. 1991; Morton et al. 1990) to be $k_1 = 1$, $k_2 = 2$, with $\tau_1 = 45$ days and $\tau_2 = 15$ days. The parameter vector changes with an individual's changing growth in capability, and is usually reset from iterative modeling of the most recent training and taper.

A training theory also requires that a standard format or formats of training should be available to effect a recognizable systems response to it. For example, the response to a square-wave stimulus of heavy training is an exp growth curve for physiological attributes and a decay curve for physical performance. The response may now be expressed both mathematically and quantitatively and be observed during its development (Booth 1977). Successive square-wave increments in training separated by tapers offer careful control of growth in performance to be exercised with overtraining and injury substantially avoided. An increase in the level of intensity and duration of training (Dudley et al. 1982; Terjung 1979) beyond the current level of activity practiced is needed to induce Morton 1991, failure of currently

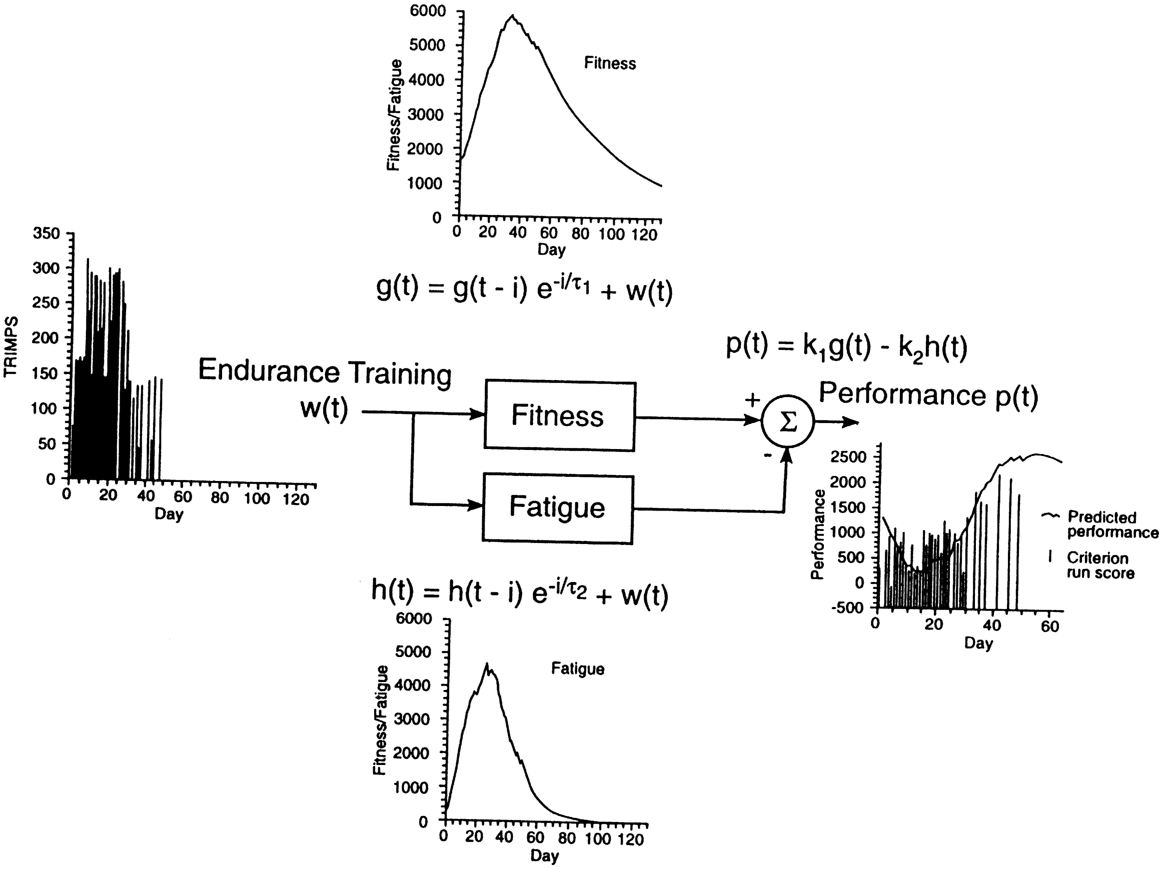

Fig. 1 A systems model of training showing transformation of the time course of a training impulse (TRIMP; left middle) into fitness [g(t)] (top-middle) and fatigue [h(t)] (bottom-middle) impulses that determine predicted performance [p(t)] (right) from the systems diagram and equations of the model (center). w(t) defines the Temp score at any time t; i is the time in days or fractions thereof between training sessions. Reprinted from Banister and Fitz-Clarke (1993) with permission from Elsevier Science

available body systems and metabolic resources to meet the new sustained energetic demand. This results in focal muscle tissue disruption, satellite cell activation (Darr and Schultz 1987; McCormick and Thomas 1992) and focal inflammatory responses at many points that induce a biological stimulus to express new proteins and enzymes to meet the increased metabolic and structural demands and to effect repair, remodeling and nutrition of tissue form and function (Armstrong 1990; Beisel 1977; Gleeson et al. 1995; Mader 1988, Parry-Billings et al. 1992).

Paradoxically, although one trains to improve the physical response, initially the opposite effect takes place and the onset of a step increase in training quantity, sufficient to improve a trainee's physical performance above the current level, is characterized by a developing fatigue throughout the set period of intense training, until a taper reveals the extent of the physical and metabolic improvement induced. If the training stimulus is too harsh or too prolonged, however, the attempted tissue regeneration and adaptation degenerates into a pathophysiological state of overtraining, producing an excessive and damaging immune system response, chronic tissue disruption, possibly overt injury, and a general malaise. Each step increment in training must therefore be imposed at a steady level, probably for no longer than 30–40 days before a taper lasting from 10 days to 14 days is completed to determine the level of improvement effected by the training just completed, in a previously measured standard criterion physical performance. Programmed tapers introduced periodically into ongoing training, besides allowing a quantitative assessment of progress, provide protection from the pathophysiology of overtraining. These features of training theory are implicit in several papers in the recent literature (Booth 1977; Calvert et al. 1976; Dudley et al. 1982; Terjung 1979).

Simulation study

Figure 2 (A–D) shows a mathematical simulation of the time course of p(t), for several types of theoretical taper from a standard quantity of daily training [w(t), 300 training impulses daily, in AUs] held constant for 28 days. The pattern of the p(t) score in AUs from the training theory outlined above indicates that the final value of the dashed line on the p(t) scale, resulting from the exponential decay time constant ($\tau = 5$ days) taper (Fig. 2B) is superior to a single step reduction in training taper (Fig. 2A). Theory also predicts that a fast ex-

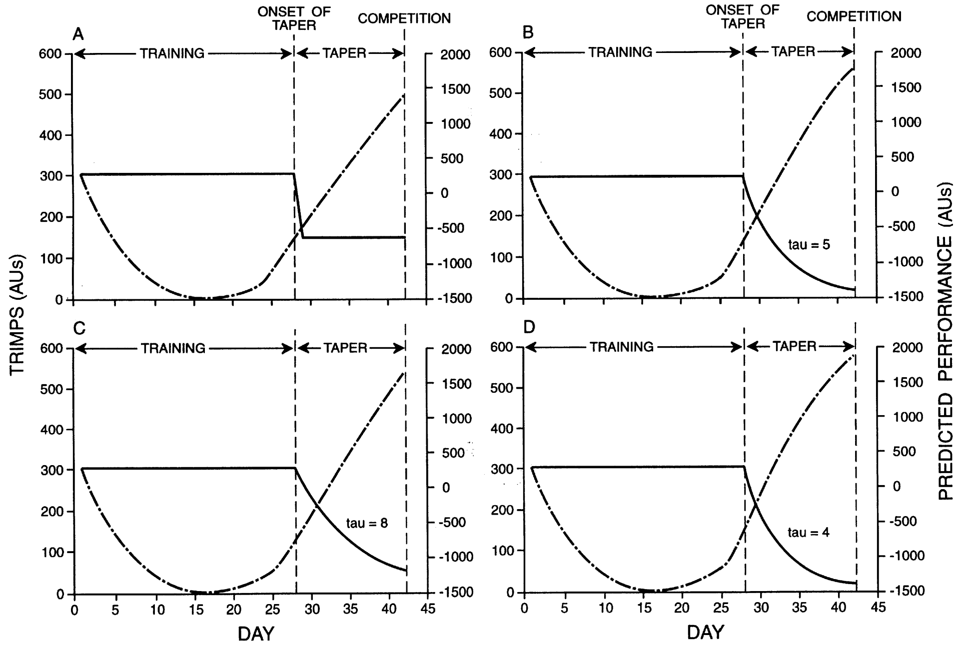

Fig. 2 Simulation of p(t) from a square-wave block of 300 TRIMPS for 28 days followed by various formats of taper. p(t) is shown by the *dashed line* and is expressed in arbitrary units (AUs). The relative effectiveness of the different formats of taper is shown by the intersection point of the various p(t) curves with the right ordinate scale, at the completion of taper

ponential decay ($\tau = 4$ days) taper (Fig. 2D) is superior to a slow exponential decay ($\tau = 8$ days) taper (Fig. 2C) in optimizing p(t). The predicted effect of the various conditions of taper described in Fig. 2 have been examined in a field trial with a cohort of 11 triathletes training for a total period of 94 days with taper to optimize performance at two real competitions spaced 42 days apart.

Methods

Field trials

Subjects

Eleven male triathletes [mean (SD)], age 26 (4) years, body fat 8.7 (1.4)%, and body mass 77.0 (6.5) kg volunteered to take part in this study. They gave their written consent after being medically approved by a physician and after having been fully informed of the nature, risks and benefits of their participation. All tests performed on the subjects received the approval of Simon Fraser University's Human Subjects Ethics Approval Committee.

Quantifying training dose

A systems model of training (Morton et al. 1990) as described above was used to quantify the pattern and size of the training stimulus and taper. In the system, a training stimulus [w(t)] is quantified and presented as a TRIMP expressed AUs. A single training bout is measured in AUs by the product of the duration of the session (D) in minutes and the ratio of exercise heart rate (HRex) to maximum heart rate (HRmax), both above a resting value (HRrest). The latter measure is termed the delta heart rate ratio (ΔHR ratio). Thus, training undertaken at any time may be expressed as an area under the curve represented by the pseudointegral:

$$\begin{aligned} w(t) &= D \times \frac{HRex - HRest}{HRmax - HRest} \\ &= D \times \Delta\ HR\ ratio \end{aligned}$$

An intensity factor Y appropriate to the degree of metabolic arousal of a subject, reflected by the Δ HR ratio is used to correct the inaccuracy arising from the using the simple heart rate response as a measure of the intensity of training. The metabolic intensity factor Y is based upon the exp rise of blood lactate levels with the fractional elevation of exercise heart rate above rest (Green et al. 1983) and gives more quantitative credit to intense training that may be short-lived, but is more metabolically stimulating and provides a substantial TRIMP. Thus overall:

$$w(t) = D \times \Delta\ HR\ ratio \times \mathrm{Y} \qquad (1)$$

Validation study design

The experiment lasted approximately 94 days (allowing for the sometimes unscheduled delays of a field study) and required each athlete to follow two separate periods of heavy training (Taper 1 trial and Taper 2 trial) each followed by a taper with performance evaluation on designated tests before a genuine triathlon competition. Taper 1 subjects were randomly assigned to one of two taper groups, matched for group mean age, weight, and initial criterion performance ability in a 5-km run for time and a ramp cycle ergometry test to exhaustion. Group 1 subjects ($n = 5$) maintained a single mean, step-reduction taper in training, from day 31, of 22% of their mean initial training volume throughout a period of 2 weeks from the onset of taper. During this first taper period (Taper 1) two subjects in group 1 had minor injuries and were not included in the first group taper, but they were able to resume their participation in the study upon recovery. Group 2 athletes ($n = 6$) tapered their training volume exply ($\tau = 5$ days) from day 31 for 2 weeks for a total reduction in training of 31% of the mean daily training average completed up to day 31. The difference between groups 1 and 2 mean training volume during taper was not significant. A short-course triathlon competition followed the Taper 1 trial preparation.

Following the mid-season short-course triathlon competition heavy training was resumed for 33 days from day 49 to day 81 after a short unprogrammed period of recovery training following the triathlon. During this time the main athlete cohort was reconstituted and athletes were assigned for the Taper 2 trial either to group A ($n = 5$), a slow exponential decay time constant ($\tau = 8$ days) taper group or to group B ($n = 6$), a fast exponential decay time constant ($\tau = 4$ days) taper group from day 81 in a final 2-week taper period. Group A athletes reduced their training volume during taper by 50% of the group mean daily training dose, and group B athletes reduced their training volume throughout taper by 65% of the group mean daily training dose. The difference in reduced training volume between groups was not significantly different. The groups were compared for the effectiveness of each taper format in producing a greater improvement, above respective pre-taper, training criterion performance measures (5-km run, maximum cycle ergometry) made in the last week of training before 2 weeks of taper. The change in parameter vector illustrates the individual or group plasticity of the response to the applied training stimulus.

Parameter vector designation

The serial score in the conventional units of the criterion physical performances [5-km run (s), maximum exhaustive cycle ergometry (Watts)] measured for each individual weekly, throughout training, defined each individual's real time course pattern of response to the several changes in the training pattern (hard training stimulus; Taper 1: step increase to a harder training stimulus; Taper 2). The parameter vector for each trainee was modeled beginning with the default parameters $k_1 = 1$, $k_2 = 2$, $\tau_1 = 45$ days, $\tau_2 = 15$ days, followed by iteratively changing each parameter until a best fit of p(t), the time course of predicted response to the training impulse profile, matched the individual's real pattern of response in the criterion physical tests of running and cycle ergometry. The group mean (SD) of each parameter value of the parameter vector throughout representative periods of each stage of training and taper was calculated from the individual responses ($n = 11$).

Training heart rate

Throughout training the heart rate for each athlete's workout was recorded at 1-min intervals by telemetry (Polar Vantage XL, Polar CIC, Port Washington N.Y., USA) in serial, daily files for weekly downloading to a computer.

Criterion physical performance

In order to monitor serial changes in physical performance, at least one and sometimes two 5-km criterion runs were performed each week to the best of the subject's current ability while training hard. Subjects ran all out on their own 5-km course, which was chosen to be as flat as possible, unobstructed by traffic (etc). Each subject ran this course weekly, with their best effort, regardless of the particular point in their training program. On another day of the week during training and taper an exhaustive cycle ergometry test was completed. During the Taper 2 trial criterion tests were made during the last week of training and during each week of final taper in which respiratory gas exchange (RGE) was also measured, during cycle ergometry, in the last week of training and in each of the subsequent 2 weeks of final taper.

Ergometry

The cycle ramp test to exhaustion was performed on an ergometer (Lode: Groningen, The Netherlands) which was electromagnetically braked and externally controlled by a computer. The ramp test protocol consisted of a 4-min warm-up period at a work rate of 30 W followed by a 30-W/min ramp increase in work rate until exhaustion or until a subject could not maintain the pedal rate above 80 rpm.

Respiratory gas exchange

During three ramp ergometry tests, one in the last week of training, prior to two more, during each of 2 weeks of taper in the Taper 2 trial, real time breath-by-breath oxygen consumption ($\dot{V}O_2$) data were measured (Linnarsson 1974). Compensation was made for functional residual capacity fluctuation, gas transport time, breathing valve dead space, and analyzer response time. Data acquisition was by a Macintosh computer (IIfx) equipped with an A,D board (National Instruments, NB-MIO-16) and a software package (National Instruments LabView II). Expiratory timing (via a sail switch), expiration flow rate (via a modified Alpha Technologies Ventilation Module VMM110), expired oxygen (Applied Electrochemistry, model S-3A) and expired carbon dioxide (Applied Electrochemistry model CD-3A) were recorded at 112 Hz (each channel) for each breath. Total breath time and expired breath time were recorded from the binary signal of the expiration sail switch. Inspired ventilation (Alpha Technologies turbine), heart rate (Physio Control monitor), work rate and minute cycle ergometer pedal revolution (Lode, The Netherlands) were recorded for each breath. A classical Douglas-bag minute collection procedure correlated with minute ventilation (0.996), modelling with $\dot{V}O_2$ (0.996), and with Carbon dioxide output (0.995), measured by the breath-by-breath computerized procedure.

Modeling and statistics

The serial score in absolute units of the maximum physical performance tests, a 5-km run time trial (s) and maximum attained ergometry work rate (W), was used to characterize the real time course of each criterion test against which p(t) from w(t), in AUs of the TRIMP score was modeled to fit the pattern of measured variation in criterion performance tests. Modeling to fit the p(t) time course to the real measured time course of a criterion physical test (CP) was effected from iterative modification of the parameter vector values τ_1, τ_2, k_1, k_2, until a best fit of P(t) to real values (CP) from the iterative procedure, minimized the sum of the squared deviations $\sum_{j=0}^{j=j}[CP_{(j)} - P_{(j)}]^2$, where j is the number of observations made of predicted performance p(t) coincident with times of real criterion performances CP(t).

During the immediate pre-taper training week and during each week of taper in both the Taper 1 and Taper 2 trials, the respective groups, groups 1 and 2 and A and B, were statistically compared using a paired t-test for significance. The difference compared was the improvement upon physical criterion tests and RGE measures during 2 separate final taper weeks, above a corresponding, final pre-taper training week measure. These differences were evaluated using a generalized linear model to account for the unbalanced number of subjects in each group, and a paired t-test. A level of significance ($P \leq 0.05$) was accepted as denoting a significant difference between any two group statistic compared.

Results

Taper 1

The modeled mean TRIMP and taper time course (AUs) for the Taper 1 trial, groups 1 and 2, during the first 42 days of the study are shown by thin vertical full lines in Fig. 3 (top panels). The group 2 exponential decay ($\tau = 5$ days) pattern of taper (top right panel, dashed line) that produced an average 31% reduction in daily training volume/quantity through 2 weeks of taper, also produced a superior p(t) to the group 1 step-reduction protocol (top left panel) that showed an average daily 22% reduction in training volume through 2 weeks of taper. The p(t) score from modeling training of group 2 athletes is 440 AUs higher than the group 1 p(t) at the end of the 2nd week of taper. A comparison of the improvement in real physical tests of performance (5-km run and ergometry) during taper, above a pre-taper training measure in the week immediately preceding the tapering, confirms the simulation model prediction in Fig. 2 of the superiority of the decay exponential taper over the step-reduction taper (Fig. 2 top panels, B and A). Table 1 shows details

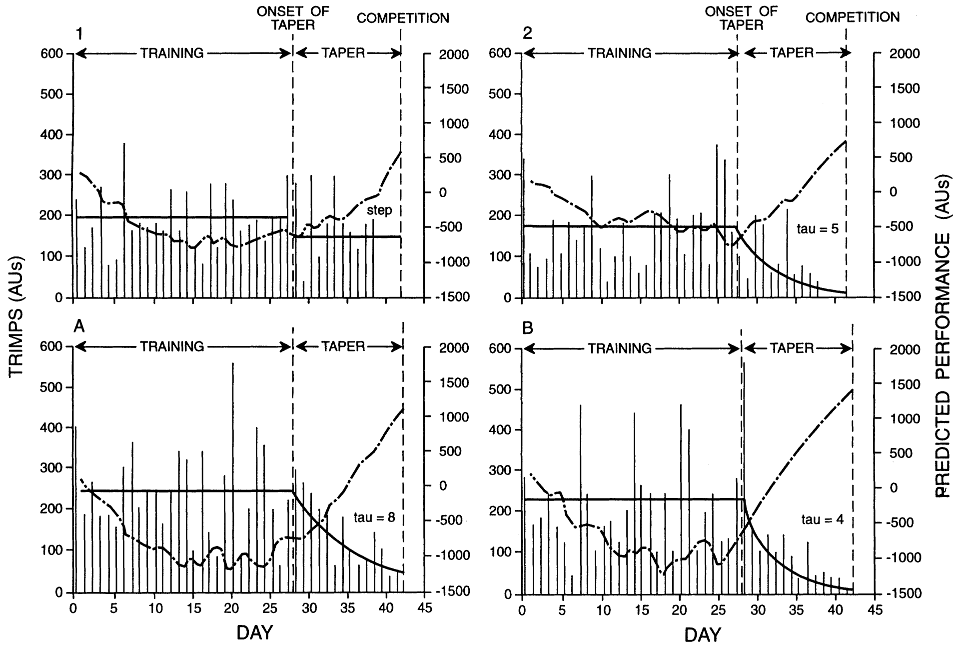

Fig. 3 Simulation of a standardized square wave (a 220-TRIMP AU average) of real training data in test groups of athletes training for a triathlon. The fast time constant taper, $\tau = 4$ days, is the more superior of these comparisons in the size of the final taper p(t), in AUs, on the right ordinate scale

Table 1 Performance measures for both a criterion 5-km run and a maximal ramp test on a cycle ergometer, in the immediate pre-taper training week and once during each week of a final 2-week taper in the Taper 1 trial for groups 1 and 2. Values are the mean (SD)

Exercise type		Step reduction taper (group 1 n = 3)			Exponential decay taper (τ = 5 days) (group 2 n = 6)		
		Pre-taper	1st week of taper	2nd week of taper	Pre-taper	1st week of taper	2nd week of taper
Run	Time (s)	1121 (56)	1106 (67)	1108 (60)	1149 (09)	1136 (86)	1103 (87)*
Cycle	Power (W)	412 (9)	–	418 (15)*	423 (25)		446 (32)**

* Significant improvement compared with pre-taper
** Significantly better group difference

of the superior performance of group 2 athletes during taper on physical criterion performance tests. There was no significant change in the intensity component of training (Δ*HR ratio* × Y) during either type of taper compared with the average intensity component of both groups' mean general training intensity. The exponential reduction in training quantity during taper was effected solely by a reduction in the duration of a training session or frequency in the number of sessions per week. Tapered training for each day was calculated from equation 2 below:

$$V_{(t)} = V_0 \, e^{-i/\tau} \tag{2}$$

where: $V_{(t)}$ is the day's calculated training dose, V_0 is the group mean daily average TRIMP amplitude (AUs) at the onset of taper, i is the day of taper, and τ is the exponential decay time constant of taper.

Taper 2

Figure 3 (Bottom, Panels A and B) shows the pattern of TRIMPs in AUs as thin vertical full lines for the re-constituted groups A and B during 42 days of training and taper in the Taper 2 trial. The superiority of the group B (fast exponential decay taper, $\tau = 4$ days) athletes' mean p(t) score (dashed line) may be compared with group A athletes (slow exponential decay taper, $\tau = 8$ days) who scored 300 AUs less than the mean group B value. The difference in total training volume between groups during the final taper was not significant, although overall the $\tau = 8$ days, slow exponential taper group reduced their training volume by 50%, measured in AUs and the $\tau = 4$ days, fast exponential taper group reduced their training volume by 65%. Training intensity (Δ *HR ratio* × Y) was maintained in both groups as training frequency decreased significantly from a training average of 5.6 (1.0) days/week to 4.4 (1.8) days/week during the last week of the Taper 2 trial. Table 2 shows details of the superior performance improvement in a 5-km run and cycle ergometry criterion performance trial made by the fast exponential decay taper group B over the slow exponential taper group A, confirming the simulation studies of these taper formats in Fig. 2 (bottom panels, B and A). Tests of significance of criterion performances between the groups were made

Table 2 Performance measures for both a criterion 5-km run and a maximal cycle ergometry test to exhaustion immediately preceding and during each of 2 final weeks of taper in the Taper 2 trial for groups A and B. Values are the mean (SD)

Exercise type		Slow taper τ = 8 days (group A, n = 5)			Fast taper τ = 4 days (group B, n = 6)		
		Pre-taper	1st Week of taper	2nd Week of taper	Pre-taper	1st Week of taper	2nd Week of taper
Run	Time (s)	1159 (60)	1142 (62)*	1131 (53)*	1167 (80)	1126 (90)*	1093 (90)*
Cycle	Power (W)	394 (45)	405 (42)	409 (33)*	433 (36)	440 (26)	467 (28)**

* Significant improvement compared with pre-taper
** Significantly better group difference

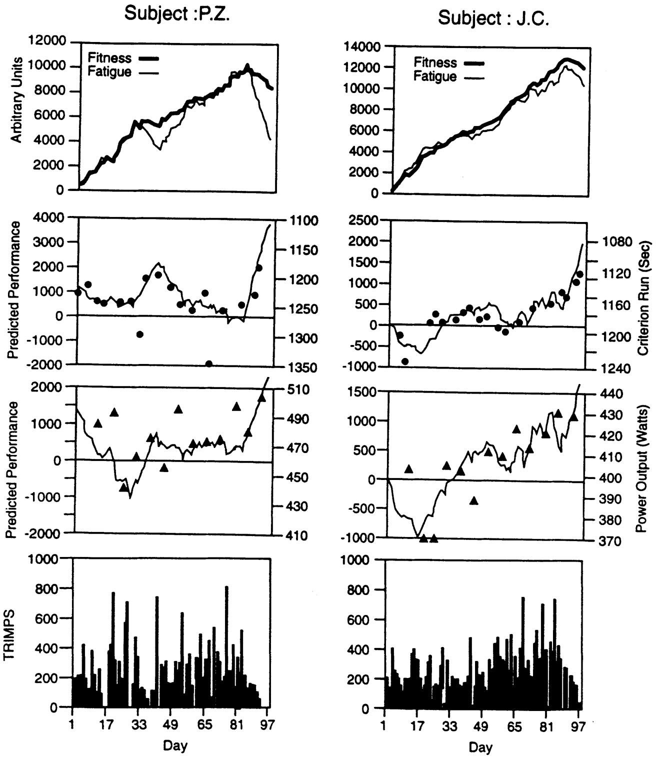

Fig. 4 Training and performance data from two typical subjects of the study showing in the bottom panels, the TRIMP [w(t)] time course which determines the fitness [g(t)] and in the top panels fatigue [h(t)] time courses (left and right respectively). p(t), shown in the middle panels as the *continuous thin line*, is modeled to match the time course of physical response in criterion real scores (CP) in a 5-km run (*solid circles*) and exhaustive ergometry (*solid triangles*)

at specific points of a standard pre-taper training day in the week of training immediately before taper commenced and on a day in each week of a subsequent 2-week taper period. Typical individual athlete responses throughout all phases of training and taper are shown for two subjects in Fig. 4.

Respiratory gas exchange

Table 3 shows the significant improvement made in $\dot{V}O_{2\,max}$ during each week of 2 final taper weeks of the Taper 2 trial above an initial $\dot{V}O_{2\,max}$ measured in the week prior to the final tapering in a group of eight athletes of the training cohort that completed both taper tests. Three remaining athletes preferred to complete the last week of taper at the Ironman competition site. The anaerobic threshold (θ_{an}), determined concurrently from RGE according to Whipp et al. (1989), also increased significantly in the last week of the Taper 2 trial.

Table 3 Relative maximum oxygen consumption ($\dot{V}O_{2\,max}$) and anaerobic threshold (θ_{an}) measured in the week immediately preceding taper and at two times in each week of a final 2-week taper in a cohort of eight subjects remaining for the last taper week of the Taper 2 trial. Values are the mean (SD)

	Pre-taper	1st Week of taper	2nd Week of taper
$\dot{V}O_{2\,max}$ (ml $\cdot$ min^{-1} $\cdot$ kg^{-1})	62.9 (5.8)	67.4 (5.6)*	68.6 (4.2)*
θ_{an} (% of $\dot{V}O_{2\,max}$)	71 (8)	73 (6)	75 (6)*

* Significantly larger than pre-taper, paired t-test

Discussion

The criterion performance improvements shown in Tables 1 and 2 are similar to those reported in many other studies on runners (Houmard 1991; Houmard et al. 1992, 1994; Shepley et al. 1992) and swimmers (Houmard and Johns 1994) on the effectiveness of taper in enhancing competitive performance. However, in no previous study has the type of response that may be expected to result from various types of quantified training and taper formats been characterized, or the predictions quantitatively confirmed, in field trials. The present study compared the effectiveness of a step decrease and various values of exp decay time constant protocols for their effectiveness in producing the best physical and physiological improvement possible from a standard square wave of training between 200 and 250 AUs per 28 days of training and 2 weeks of taper. The group comparisons described in the Results section above confirmed the finding of a simulation study, undertaken prior to the field studies, that an exponential decay taper protocol of training following a standard square-wave quantity of training is superior to a step-decrement taper in producing a better physical performance during the last week of the Taper 1 trial. A fast exponential decay taper ($\tau = 4$ days) is also superior to ac less fast exponential decay taper in improving the performance return from a standard square-wave quantity of training, as was shown in the Taper 2 trial.

Taper volume

The results of both the Taper 1 and Taper 2 trials suggest that an additional training volume in the days immediately preceding competition, whether it is due to an inadequate step reduction in training or to a slower exponential decay taper, is detrimental to the physical performance achieved in a criterion test. It is apparent from the present results, and it has been shown abundantly by others, that the effect of step-reduced training (Hickson et al. 1982, 1985; Houmard 1990a; McConnell et al. 1993; Neufer 1989; Neufer et al. 1987) and taper training (Houmard et al. 1992; Shepley et al. 1992) is to allow training volume, with maintained intensity, to be reduced by as much or more than 50% from its previous average, with optimal results during the final days before competition. The frequency of training in both Taper 1 and Taper 2 trials of the present study was respectively decreased significantly by 1 day/week in the final half of each taper period as training volume reduced throughout the taper. Since no concomitant impairment in performance was observed, it may be beneficial for an athlete to supplement a fast decay exp taper further with 1 or 2 interpolated days of complete rest in the week prior to competition. This may allow maximal recovery from training fatigue and further optimize preparation for competition.

Previous studies are sometimes difficult to interpret or compare precisely with the present experiment since they define training volume/quantity, variously, by time, distance, intensity of effort, frequency of effort, or by combinations of these variables. These characterizations of quantity are imprecise since quantity depends upon both the duration and intensity of an activity (see eq. 1), and duration itself is a product of session duration and session frequency. Intensity is a complex of heart rate elevation and a true metabolic arousal factor (Y), defined in the present study from the ΔHR ratio and the exponential rise of blood lactate levels as heart rate increases with increasing metabolic effort (Green et al. 1983).

Taper intensity

The group mean intensity of training during both Taper 1 and Taper 2 trials, measured quantitatively from the telemetered heart rate of the individual trainees during criterion physical tests, did not change compared with the average rate during training. Exercise intensity (metabolic arousal) is a key factor in either maintaining (Dudley et al. 1982; Houmard et al. 1990a), or losing physical ability (Hickson et al. 1985; McConnell et al. 1993), and much of the performance improvement in the present study may be attributed to the maintenance of intense training during both Taper 1 and Taper 2 trials. A serial criterion performance measurement repeated one to two times/week during taper, besides being a key factor in providing the necessary intensity of training during taper, was also a means by which to assess serial changes in the performance ability of the trainees. Results from this study suggest that an optimal taper requires a sufficient decay in training volume ($\leq$ 50% reduction), while the intensity of training is maintained at or above 70% of the Δ HR ratio in order to observe the best improvement return in physical performance for the effort expended in training. For a given volume of training, if intensity is increased, the duration or the frequency of a session per day or week must decrease significantly. During a taper of high intensity a complete day's rest from training may be occasionally interpolated in the taper regimen.

Cardiorespiratory results

Relative $\dot{V}O_{2\,max}$ measured on a maximal ramp test to exhaustion in eight subjects, significantly increased during the final 2-week taper (Taper 2 trial). $\dot{V}O_{2\,max}$ increased from 62.9 (5.8) ml $\cdot$ min^{-1} $\cdot$ kg^{-1}, measured 2 weeks prior to taper, to a significantly higher value of 67.4 (5.6) ml $\cdot$ min^{-1} $\cdot$ kg^{-1} during the 1st week of taper, and 68.6 (4.2) ml $\cdot$ min^{-1} $\cdot$ kg^{-1} during the 2nd week of taper. An increase in $\dot{V}O_{2\,max}$ with taper has not been previously reported in the literature although $\dot{V}O_{2\,max}$ has been reported to increase with training (Neufer 1989) and decrease with a prolonged reduction in training volume (Hickson et al. 1982). Recent taper studies have reported improvements in physical performance with no increase in $\dot{V}O_{2\,max}$ (Houmard et al. 1992; O'Toole and Douglas 1995). These latter treadmill studies, however, have either constrained the subject to run at a fixed speed uphill or have allowed the athletes themselves control the speed. These responsibilities are distracting to a performer and cast doubt on the ability of a subject to run maximally under such conditions. It also appears that training intensity is a key factor in maintaining aerobic power in a competitor (Hickson et al. 1982). The reported 9% increase in $\dot{V}O_{2\,max}$ observed in the latter study between a pre-taper, training test and a final week of taper test, is very similar to the 8% increase in maximal power output on the cycle ergometer in the fast exponential decay taper group of the present study.

The θ_{an} determined by a non-invasive technique described by Whipp et al. (1989), improved from 71% of $\dot{V}O_{2\,max}$ to a significantly higher value of 75% of $\dot{V}O_{2\,max}$. An improvement in the θ_{an} has not been previously reported with taper. These values are somewhat less than the 83% of $\dot{V}O_{2\,max}$ reported previously by Medelli et al. (1993) in highly trained triathletes, probably due the lower absolute ability level of the present subjects.

Plasticity of the training response

Whether the response exhibits plasticity is established if an individual responds with the same degree and pattern of response, on measured variables (physical, physiological, biochemical) to equal quantities of training. These quantities of training must be presented sequentially, but separated by a non-training period that is long enough (at least 2 months) for any part of the previous trained state to have dissipated. Do different individuals respond similarly to equal doses of training? This seems to be the case in one quantitative study made to date, but with only two subjects (Banister and Fitz-Clarke 1993). Resetting the parameter vector of the model variables as a person progresses in a coherent progressive training program offers beginning insight into the degree of change in a trainee of the attributes designated fitness and fatigue in the present model of training. A consistent change in the parameter vector was needed to fit each subject's p(t) time course to real performance through the different phases of the 94-day experiment. The observations (Table 4) were that the group mean fitness multiplier varied little throughout the different phases of training and taper. The fatigue multiplier was sensitive to both types of exercise, responding to heavy training with an increase in the multiplier and to taper with a decrease. Viewed in the longer term, k_2 gradually increased consistently with the increased training load. The change in the time constant parameters τ_1 and τ_2 were out of phase: τ_1 increased with each taper phase and decreased throughout imposed heavy training, whereas τ_2 changed in the opposite manner. These changes probably reflect the increasing volume of training undertaken in progressive training and presents the problem, faced by every trainee, of how to keep increasing the severity of training in order to continue to improve to some predisposing genetic limit. Several more turns of the on/off training and taper cycle described in the present experiment should define the time course of parameter vector change more clearly.

As suggested above, theoretically, the long-term expectation from step-incremented training is to increase the training stimulus to a subject's genetic limit of response. Training at such a level will need several sessions per day to be practiced otherwise both the quantity and declining intensity of effort able to be practiced in as long, or a longer session will be insufficient to raise the performance response. A rest pause between each adequate training session of at least 3–4 h will be needed to return the necessary vitality to the trainee, enabling practice at the same intensity of effort even for a reduced period during succeeding sessions. Perhaps three to five sessions per day of high-intensity training would eventually be tolerated.

During taper, as the training stimulus declines we should expect k_2 to become longer as training becomes really severe, and τ_2 becomes longer because the fatigue of training really becomes difficult to shed. Nevertheless, τ_1 becomes longer as fitness accumulates from the large volume of training undertaken. During taper, as training declines, τ_2 and k_2 might be expected to reduce since a high level of fitness will obscure the declining effect of fatigue. In the present experiment it seems that the quantity of training may not have been high enough to effect a marked response in the group mean parameter vector through the different phases of hard training and taper. Table 4 shows that parameter vector modeling training w(t) in individuals, to fit a trainee's p(t) to mirror the pattern of real performance in both a 5-km run (s) and maximum cycle ergometry (W) during 10-day periods in each training and taper phase of the two taper trials, does seem to react in the above manner: τ_1 does not change initially, k_2 grows throughout, τ_1 grows indicating that fitness is well retained, although fatigue from training and taper is also prolonged as τ_2 lengthens; compared with the slowness of the decay of fitness, the decay of fatigue is still relatively much faster.

Table 4 Change in the group mean parameter vector for a 10-day period throughout each phase of training and taper in Taper trials 1 and 2. The group mean change was derived directly by measuring the parameter vector of each trainee response to training during each of the time intervals, by modeling each individual's predicted performance, p(t) to their real pattern of criterion performances in running (5 km s) and (ergometry, W). The group mean (SD) of the individual results are shown. τ_1, τ_2 are time constants for the decay of fitness and fatigue, respectively. k_1, k_2 are arbitrary multipliers converting a TRIMP score to hypothesized impulses of fitness and fatigue experienced by a trainee

Parameter Vector		k_1	k_2	τ_1	τ_2
Run	Train	1	1.8 (0.2)	45	16 (2)
	Taper 1	1	1.8 (0.2)	51 (3)	15 (4)
	Train	1	1.9 (0.2)	46 (2)	21 (4)
	Taper 2	1	1.9 (0.2)	52 (3)	17 (3)
Cycle	Train	1	1.8 (0.2)	45	16 (3)
	Taper 1	1	1.8 (0.2)	51 (2)	16 (3)
	Train	1	1.8 (0.2)	45 (2)	19 (4)
	Taper 2	1	2.0 (0.4)	52 (3)	17 (4)

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